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Total Maximum Daily Load
Phosphorus Study

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Moses Lake
Total Maximum Daily Load
Phosphorus Study

by
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Olympia, Washington 98504-7710

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Abstract

Moses Lake and its watershed have been altered by human activities, especially irrigation, lake phosphorus dilution with irrigation feed water, and urban development. The last intensive water quality study of Moses Lake was completed in 1988, summarized by Welch et al. (1989; 1992). This current report updates that work and complements the historical review and preliminary TMDL evaluation by Carroll et al. (2000).

Intensive sampling of Moses Lake and its vicinity was conducted from October 2000 through September 2001 to assess the status of the lake and its tributaries. The mean total phosphorus (TP) concentration for the whole lake from May through September was 38 ug/L. This report recommends establishing a seasonal water quality TP criterion of 50 ug/L for Moses Lake.

A hydrodynamic, unsteady-state water quality model was developed for Moses Lake and calibrated to the 2001 water quality data. The model was used to estimate the capacity of the lake to assimilate TP loads from point and nonpoint sources and meet the recommended water quality criterion.

Using critical loading conditions, the lake model showed that a 35% load reduction in TP from Rocky Ford Creek, Crab Creek, Rocky Coulee Wasteway baseflow, and groundwater was necessary to meet the proposed TP criterion with only a 10% exceedance probability. Further reductions in external phosphorus loads only marginally reduced TP concentrations in the lake because under these conditions internal sources begin to dominate in-lake concentrations.

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Introduction

Problem Statement

The Washington State Department of Ecology (Ecology) recognizes Moses Lake as an important natural resource of Washington State, providing wildlife habitat, recreation, and water supply. Ecology's Eastern Regional Office (ERO) is concerned about the water quality in Moses Lake which is on the 1996 303(d) list for total nitrogen and total phosphorus (TP). Several restoration projects have been conducted on Moses Lake and its watershed over the last 20 years, including lake dilution (with inter-basin pumping), sewage diversion, agricultural best management practices, and construction of a tributary nutrient retention pond. Despite improvement in lake water quality as a result of these projects, total nitrogen and TP levels remain elevated, resulting in the persistence of blue-green algae blooms (Welch et al., 1989, 1992; Jones and Welch, 1990).

As a result, ERO requested that Ecology's Environmental Assessment (EA) Program report on the status of Moses Lake water quality and, if possible, develop a total maximum daily load (TMDL) for nutrient loading to the lake based on historical data (no new data collection). The federal Clean Water Act requires Washington State to establish a TMDL for each pollutant on the 303(d) list. The TMDL is apportioned between point and nonpoint sources as wasteload and load allocations, respectively. The primary goal of the ERO request was to have the EA Program develop an allocation strategy that could be used to improve lake water quality and ultimately lead to removing Moses Lake from the 303(d) list. The EA Program completed the report, *Moses Lake Proposed Phosphorus Criterion and Preliminary Load Allocations Based on Historical Data,* in October 2000 (Carroll et al., 2000).

Although Moses Lake is listed for both TP and total nitrogen on the 303(d) list, historical studies on Moses Lake reviewed in the 2000 report show that TP is the appropriate nutrient to control to limit algal biomass. The strategy of managing TP to control algal biomass is supported in the literature, even for lakes where nitrogen may be temporarily limiting the growth rate. On this basis, the 2000 report recommended that Moses Lake be de-listed for total nitrogen from the 303(d) list and that future lake management activities and decisions focus on the control of TP to manage algal biomass in Moses Lake.

While the 2000 report presented preliminary phosphorus allocations, a major conclusion was that additional work should be completed before establishing a final TMDL and allocation strategy for the lake. The report recommended additional data collection so that the results could be used, with the historical data, to finalize an allocation plan.

The following were the major reasons for collecting additional data:

- No comprehensive water quality assessment of the lake has been done since 1988. Multiple sources of data were used to develop the historical work, now 15 years old.
- New water quality data, together with findings and recommendations from historical studies, are needed to set a nutrient TMDL for the lake.

- A TP TMDL for Moses Lake is needed to satisfy the requirement of the federal Clean Water Act and to help meet water quality goals established for the lake by previous studies.

Beneficial Uses and 303(d) Listings

Moses Lake is classified as Lake class under Washington State water quality standards (Chapter 173-201A WAC). Rocky Ford Creek is classified as Class A, and Crab Creek as Class B. Lake class and Class A waters are required to meet or exceed the requirements for all, or substantially all, of the following characteristic uses: domestic, industrial, and agricultural water supply; stock watering; salmonid and other fish migration, rearing, spawning, and harvesting; wildlife habitat; recreation (primary-contact recreation, sport fishing, boating, and aesthetic enjoyment); and commerce and navigation. Class B waters are required to meet or exceed the requirements for most of the preceding uses.

Moses Lake was first listed on the 1996 303(d) list as not supporting characteristic uses because of excess total nitrogen and TP. The water quality criterion for Lake class calls for no measurable change from natural conditions. Carroll et al. (2000) proposed the establishment of nutrient criteria for Moses Lake, with which this report concurs in establishing nutrient loading allocations. Rocky Ford Creek is presently listed for violations of temperature, dissolved oxygen, and pH criteria. Cusimano and Ward (1998) investigated the causes of these listings. The upper part of Crab Creek is presently listed for violations of pH criterion.

Brief History of Moses Lake

Moses Lake is a natural lake originally created by wind-blown sand dunes which dammed part of the Crab Creek watershed. As one of the largest lakes in Washington State, Moses Lake is an important natural resource providing recreational and aesthetic opportunities. The primary water quality problem identified in the historical studies of Moses Lake is the hypereutrophic blooms of blue-green algae, which can impair recreational uses of the lake during the summer months (Carroll et al, 2000).

As a large, shallow hypereutrophic lake, Moses Lake has garnered the attention of limnologists and engineers in the last 30 years as a candidate for lake restoration, which has resulted in many studies. Blue-green algae have been observed to form into floating mats to be blown onto the shore to decompose as recently as 1998 (Smith et al, 2000).

Moses Lake and its watershed have been altered since the inception of the Columbia Basin Irrigation Project (CBIP) in the early 1950s, when the U.S. Bureau of Reclamation (USBR) began importing Columbia River water into the upper Crab Creek watershed to promote the development of irrigated cropland. Previous studies indicated that anthropogenic (human) activities, primarily agricultural practices and operations associated with the CBIP, were creating a hypereutrophic state in Moses Lake through nutrient enrichment.

Welch et al. (1989; 1992), Jones and Welch (1990), and Carroll et al. (2000) provide detailed review of historical studies of the lake and its watershed, and beneficial uses of the lake.

Project Goal

The major goal of this current study was to assess the assimilative capacity of Moses Lake with respect to the in-lake proposed TP criterion of 50 ug/L. Data were collected and used in this assessment. A TP allocation plan is recommended to achieve the in-lake TP criterion.

Project Objectives

- Assess the current water quality condition of Moses Lake by conducting surface and groundwater quality surveys.
- Measure lake inflows and outflows.
- Identify TP watershed loading contributions to the lake from surface and groundwater sources.
- Develop an approach for modeling the water quality of the lake, then use the model to assess the capacity of the lake to assimilate TP with respect to maintaining the in-lake TP criterion of 50 ug/L.
- Develop a phosphorus allocation plan based on meeting the in-lake proposed TP criterion of 50 ug/L.

The TMDL Process

Section 303(d) of the federal Clean Water Act requires states to implement water-quality-based pollution controls on waterbody segments where technology-based controls are insufficient to achieve water quality standards. To meet this requirement, a total maximum daily load (TMDL) must be established for each pollutant violating water quality criteria. The TMDL is then apportioned between point and nonpoint sources as wasteload and load allocations, respectively. A margin of safety is also apportioned into the TMDL to account for uncertainty related to critical conditions, causes of the water quality problem, and loading capacity for the waterbody. Allocations are implemented through NPDES permits and nonpoint source controls. The goal of the TMDL is to bring waterbodies into compliance with water quality standards.

Study Design and Methods

Design

Carroll et al. (2000) recommended that a dynamic computer model for Moses Lake be developed to look at the seasonal and spatial effects of annual phosphorus loading changes throughout the entire lake. Under this study plan, the EA Program's Watershed Ecology Section (WES) assessed the tributary loading to Moses Lake for one year (October 2000 through September 2001) and monitored lake water quality monthly from March through September 2001 to develop a model of the lake, in order to simulate the hydrodynamics and estimate the water column TP concentration. Tributary sampling surveys occurred monthly from October 2000 through February 2001 as part of routine monthly monitoring conducted by Ecology. More intensive surveys of the tributaries and the lake occurred twice per month from March through September 2001.

Methods

Field Sampling

Figure 1 shows the lake and tributary sampling locations. The Quality Assurance (QA) Project Plan (Carroll, 2001) for this study listed the tributary and lake sampling stations that WES monitored. Sampling station continuity with earlier historical sampling stations was intended where applicable. The QA Project Plan lists the parameters and frequency of monitoring. During the synoptic surveys, grab samples were collected once or twice a day from the tributary stations on the first day of the survey, and once from each of the lake stations on the second day of the survey.

As part of this project, the EA Program's Environmental Monitoring and Trends Section (EMTS) sampled three tributary and one lake sampling station from October 2000 through September 2001, once per month:

1. Rocky Ford Creek at Highway 17 (Hwy 17)
2. Crab Creek at the USGS Gaging Station at Road 7 NE (CC1)
3. Rocky Coulee Wasteway at Road K bridge (RC1)
4. Moses Lake at the Outlet (ML7)

EMTS sampled these stations for dissolved oxygen, conductivity, pH, temperature, total suspended solids, turbidity, fecal coliform bacteria, and nutrients following their quality assurance procedures (Ehinger, 1996). WES and EMTS staggered their sampling times so that these sites were monitored twice per month, approximately two weeks apart.

During each WES survey (approximately monthly from March to September), water column data were collected at 1-meter intervals at each lake station using a Hydrolab® Surveyor 2. Secchi

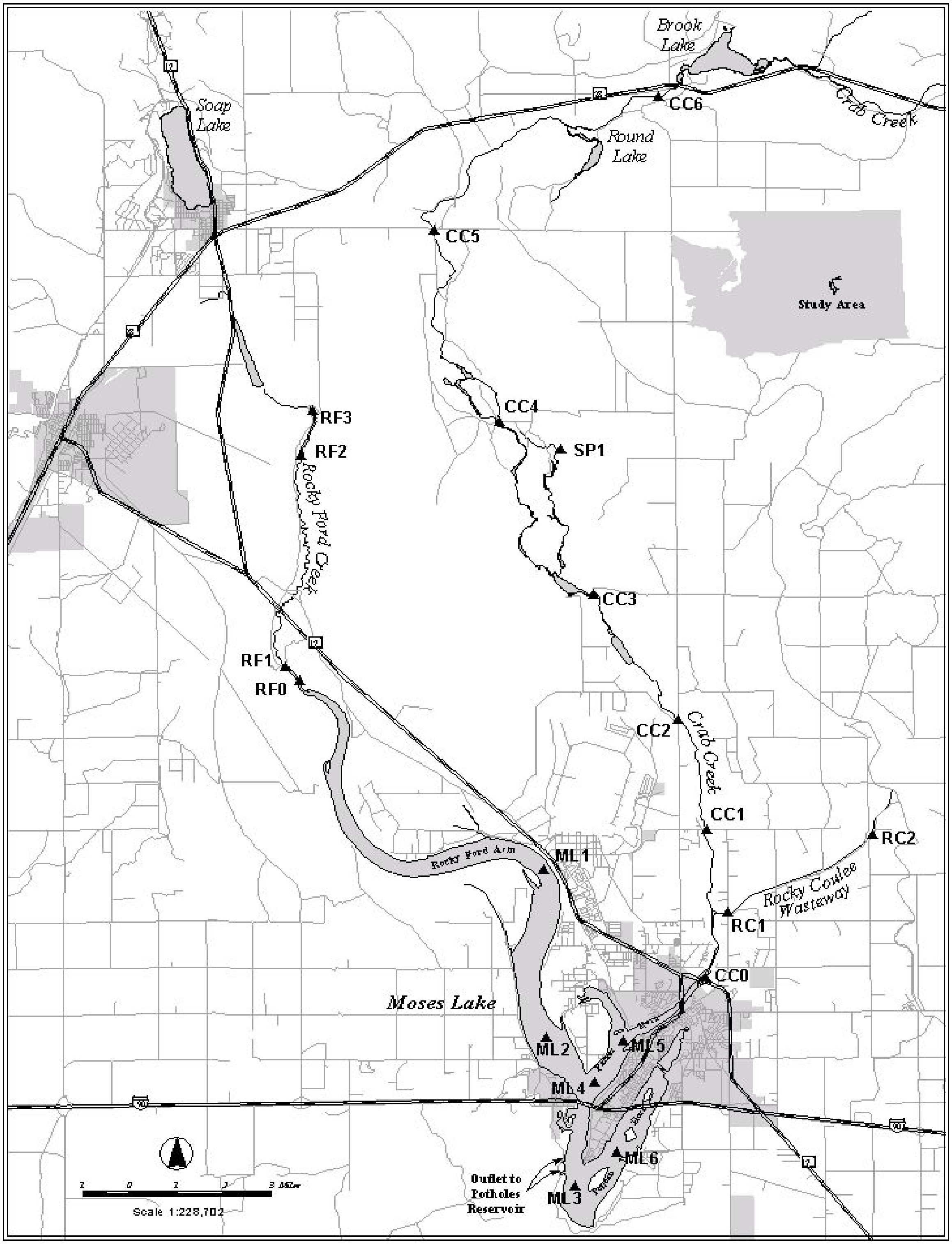


Figure 1. Vicinity map of Moses Lake and partial watershed with sampling stations. (Additional Rocky Ford Creek stations are shown in Figure 4.)

depths were measured at lake stations. Water grab samples were taken at 3 meter intervals from the surface to the bottom for laboratory analyses. In addition, *in situ* Hydrolab® dataloggers (Datasonde 3) were placed at the mouth of Crab Creek and Rocky Ford Creek to collect continuous conductivity, pH, and temperature measurements for water entering the lake from March through September 2001.

Water collection for laboratory analyses followed the design outlined in the QA Project Plan. Parameters collected included turbidity, total suspended solids, total dissolved solids, alkalinity, chlorophyll *a*, total and dissolved organic carbon, conductivity, pH, dissolved oxygen, temperature, chloride, biochemical oxygen demand, and nutrients. Nutrient analyses included total nitrogen (persulfate digestion), ammonia-N, nitrate+nitrite-N, TP, and orthophosphate (ortho-P). Ortho-P methodology measures dissolved reactive phosphorus but will be referred as ortho-P throughout this report.

Vertical profiles of light extinction were measured at all lake stations during most lake surveys. Phytoplankton samples also were collected at selected stations during each lake survey to provide data on species composition and biovolume.

The U.S. Geological Survey (USGS) maintained gaging sites on Rocky Ford Creek (USGS station 12470500; located near station RF1A on Figure 4) and on Crab Creek (USGS station 12467000; located near station CC1 on Figure 1. USGS also monitored continuous stage levels in Moses Lake.

EMTS measured tributary stream flows to the lake during the study period, October 2000 through September 2001. They recorded continuous stage height data at two stations (RF0 and RC1) and developed rating curves to calculate continuous discharge from these sites. EMTS also calculated continuous discharge data for the northern outlet (Appendix A). The outlet, operated by the Moses Lake Irrigation and Rehabilitation District, had only one culvert partially opened in a stationary position for the entire study period.

Continuous flow through the south outlet, operated by USBR, was modeled by Northwest Hydraulic Consultants using HEC-RAS version 3.0, software developed by the U.S. Corps of Engineers. Flow measurements were made by Ecology and USBR using acoustic Doppler current profilers during various flow conditions (e.g., full pool, low pool, submerged backwater, unsubmerged backwater, restricted flow, and unrestricted flow).

Groundwater discharge to Moses Lake was characterized for water quality parameters by the Watershed Ecology Section (Pitz, 2003).

Data Analysis and Lake Water Quality Modeling

All project data were entered in Microsoft Excel spreadsheets or retained in text files. Data analysis included evaluation of data distribution characteristics and, as necessary, appropriate distribution transformations. Estimation of univariate statistical parameters and graphical presentation of the data (box plots, time series, regressions) were made using SYSTAT/SYGRAPH8, EXCEL, or WQHYDRO (Aroner, 1994) computer software.

Using the tributary flow data and concentration data, a log linear regression model was used to estimate the daily fluvial loads for each tributary to Moses Lake. The log linear model requires estimation of a constant, a linear and quadratic fit to the logarithm of flow, and sinusoidal (Fourier) functions to account for the effect of annual seasonality:

$$\log(C) = b_o + b_1 * \log(Q) + b_2 * \log(Q)^2 + b_3 * \sin(2\pi T) + b_4 * \cos(2\pi T) + b_5 * \sin(4\pi T) + b_6 * \cos(4\pi T) + \varepsilon$$

Log (C) is the logarithm of each parameter concentration, log Q is the logarithm of flow, and T is time measured in years. The error term (ε) is assumed to be independent and normally distributed with zero mean. The b terms are the parameters of the model that must be estimated from multiple regressions. A simple SYSTAT code provided the regression coefficients and appropriate statistical parameters, following the approach presented in Cohn et al. (1989).

The project required a model capable of simulating the transport and fate of phosphorus in a lake environment, including a mechanism accounting for the settling and flux (release) of phosphorus to and from the sediments. In addition, the model needed to include (1) hydraulic routing as a variable that can be easily changed, due to the managed hydrology of the watershed, and (2) groundwater phosphorus loading directly to the lake.

CE-QUAL-W2 Version 3.1 was chosen to apply to Moses Lake. CE-QUAL-W2 is a two dimensional (longitudinal-vertical), laterally-averaged hydrodynamic and water quality model that has been under-development by the Corps of Engineers Waterways Experimentation Station (Cole and Wells, 2002). The model was calibrated to the field data collected during the study. The calibrated model then was used to assess the capacity of the lake to assimilate TP seasonally and spatially with respect to maintaining the in-lake TP criterion of 50 ug/L. Boundary conditions, model set-up, and calibration are discussed below.

The model results were used with the historical data to finalize an allocation plan. This allocation plan included setting load allocations and wasteload allocations necessary to meet the in-lake TP criterion of 50 ug/L.

Data Quality Objectives and Analytical Procedures

Ecology's Manchester Environmental Laboratory (MEL, 2000) publishes reporting limits for the analytical methods they perform. These reporting limits met the data quality objectives for this project. Field measurements and laboratory analyses used are listed in the QA Project Plan, including the methods, corresponding reporting limits, target precision, and target bias acceptable range.

Data Assessment Procedures

Laboratory data reduction, review, and reporting followed procedures outlined in MEL's Lab Users Manual (MEL, 2000). All water quality data were entered into Ecology's Environmental Information Management (EIM) system. Data were verified, and 100% of data entry was reviewed for errors.

Quality Assurance and Quality Control

All data collected for this Moses Lake TMDL Phosphorus Study were evaluated to determine whether data quality objectives for the project were met. Water quality objectives are described in the Quality Assurance (QA) Project Plan (Carroll, 2001).

All water samples for laboratory analysis were collected in pre-cleaned containers supplied by Ecology's Manchester Environmental Laboratory (MEL), except dissolved organic carbon and ortho-P which were collected in a syringe and filtered into a pre-cleaned container. The syringe was rinsed with ambient water at each sampling site three times before filtering. All samples for laboratory analysis were preserved as specified by MEL (MEL, 2000) and delivered to MEL within 24 hours of collection. Laboratory analyses listed in the QA Project Plan were performed in accordance with MEL (2000).

Field Parameters

Field Quality Assurance

Field sampling and measurement protocols followed were those specified in WAS (1993) for dissolved oxygen (Winkler titration), streamflow (Marsh-McBirney, 2000), and *in situ* temperature, dissolved oxygen, pH, and specific conductance (Hydrolab® multi-parameter meters).

Meters were pre- and post-calibrated for pH, dissolved oxygen, and conductivity. The manufacturer's instructions were followed for pH calibration, using pH 7 and pH 10 standard buffer solutions. All post-calibration readings were within 0.25 pH units of buffer values and were considered acceptable. Post calibration standard checks for conductivity were all within 5 µmhos/cm of the expected value and were considered acceptable.

The dissolved oxygen sensor was calibrated against theoretical water-saturated air, in accordance with manufacturer's instructions. Daily field samples were collected for Winkler titrations and check standards. Winkler titrations were judged to have greater accuracy than meter measurements. If necessary, Winkler titration dissolved oxygen measurements were used to adjust meter data for data analyses. After meter data were adjusted, all dissolved oxygen data were considered acceptable except that from March 26 – 28, 2001. The pooled average difference between Winkler and meter readings was 0.12 mg/L with a pooled RMSE of 0.44 mg/L.

Precision

Replicate samples were collected for at least 10% of the total number of laboratory samples in order to assess total variation for field sampling and laboratory analysis. Precision was estimated using replicates. Precision was calculated by pooling the %RSD for all pairs of replicates with detectable analytes. Results are listed in Table 1. As expected, %RSD for field replicates is higher than that for lab duplicates. Many of the results were heavily influenced by replicates collected on August 1, 2001. Field variation was apparently high on that date.

Table 1. Field precision. Results at the detection limit were excluded from consideration.

Parameter	Number of Duplicate Pairs	Average %RSD
Alkalinity	24	1.1
Ammonia-Nitrogen	11	50.5
Chlorides	24	3.6
Chlorophyll	22	31.9
Conductivity	23	1.1
Dissolved Organic Carbon	23	6.7
Nitrite-Nitrate Nitrogen	16	6.1
Orthophosphate	15	10.9
Total Dissolved Solids	24	3.4
Total Organic Carbon	23	4.5
Total Phosphorus (TP)	23	9.5
Total Persulfate Nitrogen	22	9.1
Total Suspended Solids	16	21.0
Turbidity	23	23.4

Bias

Field blank sample results are presented in Table 2. Except for specific conductance which was measured in two of the blank samples, all other field blanks were below reporting limits. In reviewing all field and laboratory quality control (QC) data, it does not appear that there was any contamination or positive bias in either the sampling or analytical procedures.

Table 2. Field blank results. Results qualified with a "U" or "UJ" mean that the blank had no detection at the reporting limit for the parameter, therefore reporting limit is reported as the result.

Parameter	Date	Result		
Alkalinity	06/26/01	5.0	mg/L	U
	08/01/01	5.0	mg/L	U
Ammonia-Nitrogen	06/26/01	0.010	mg/L	U
Chlorides	06/26/01	0.10	mg/L	U
	08/01/01	0.10	mg/L	U
Conductivity	06/26/01	1.53	µmhos/cm	
	08/01/01	2.7	µmhos/cm	J
Dissolved Organic Carbon	06/26/01	1.0	mg/L	U
Nitrite-Nitrate Nitrogen	06/26/01	0.010	mg/L	U
Orthophosphate	06/26/01	0.005	mg/L	U
Total Dissolved Solids	06/26/01	1.0	mg/L	U
Total Organic Carbon	06/26/01	1.0	mg/L	U
	08/01/01	1.0	mg/L	UJ
Total Phosphorus (TP)	06/26/01	0.010	mg/L	U
Total Persulfate Nitrogen	06/26/01	0.010	mg/L	U

Laboratory Parameters

Laboratory Quality Assurance

Laboratory data were generated according to QA and QC procedures followed by MEL (2000). MEL was used for all laboratory analysis. Laboratory QC requirements include the use of check standards, reference materials, samples spiked with higher concentrations, blanks, and lab split samples (duplicates). Lab splits and samples spiked with higher concentrations are discussed below. In addition, field blanks and laboratory standards (for TP) were collected to determine the presence of any positive bias in the analytical method. The phosphorus standards were included because it is the main parameter of concern for the TMDL. Replicate, blank, and standard QA samples were introduced in the field and submitted "blind" with the routine batches of samples to the laboratory.

For the most part, data quality for this project met all lab QA/QC criteria as determined by MEL. Exceptions that caused the results to be qualified as an estimate are qualified with a "J" qualifier in the data appendix (Appendix B). All qualifications were taken under consideration for the purpose of data analysis.

Results not detected at or above the reporting limits listed in the QA Project Plan were qualified by MEL with a "U." These data were excluded from consideration in determining lab and field data quality.

Lower reporting limits for all parameters were listed in the QA Project Plan. Two were listed incorrectly: turbidity, with a lower reporting limit of 0.5 NTU, and alkalinity with a lower reporting limit of 10 mg/L.

Precision

To determine precision, the relative standard deviation (%RSD—the coefficient of variation expressed as a percentage) was calculated for each pair of lab split results (with detectable levels of analytes), and the %RSDs were subsequently pooled for each parameter. In interpreting QA/QC results, it is important to note that a pair of values that are low in magnitude with a low residual may have a high %RSD, while a pair of values high in magnitude with a high residual may have a low %RSD. Results (Table 3) were all under the acceptable %RSD listed in the QA Project Plan.

In addition to duplicate samples, check standards for TP were submitted to the lab on five occasions. There was a low recovery bias (approximately 10%; CV=12.7%) as can be seen in Figure 2. QA/QC check standards should be within ±2 times the target for %RSD of the true value (Lombard and Kirchmer, 2001). All check standards fall within 20% RSD, indicating acceptable precision for TP; therefore, no correction to the data was made. Check standards are summarized in Table 4.

Table 3. Lab precision. Results at the detection limit were excluded from consideration.

Parameter	Number of Duplicate Pairs	Pooled %RSD
Alkalinity	29	0.4
Ammonia-Nitrogen	9	3.0
Chlorides	27	2.6
Chlorophyll	27	8.3
Conductivity	24	0.1
Dissolved Organic Carbon	21	2.4
Nitrite-Nitrate Nitrogen	23	6.4
Orthophosphate	19	1.2
Total Dissolved Solids	27	1.8
Total Non-Volatile Suspended Solids	10	9.5
Total Organic Carbon	22	2.4
Total Phosphorus (TP)	37	4.3
Total Phosphorus – Dissolved	7	1.9
Total Persulfate Nitrogen	32	4.1
Total Persulfate Nitrogen – Dissolved	8	1.5
Total Suspended Solids	19	3.6
Turbidity	26	1.3

Table 4. Summary of results for TP check standards.

Known Concentration (mg/L)	Pooled %RSD	Average % Recovery
0.010	6.1	101.9
0.050	10.3	93.3
0.100	6.8	95.5

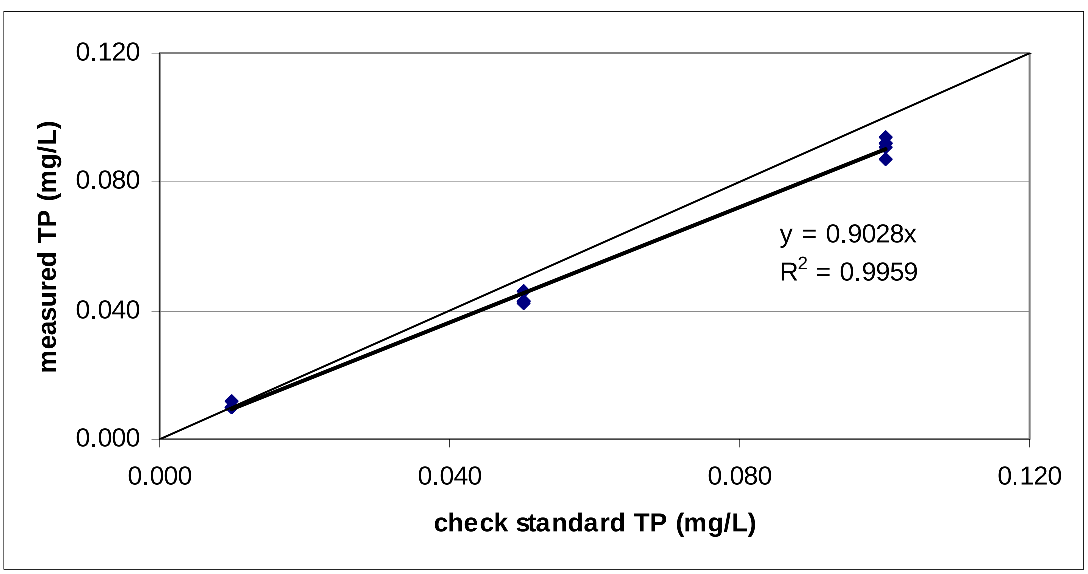


Figure 2. Check standard concentrations of TP compared to measured concentrations of TP.

Bias

Check standards also were used to evaluate bias for TP. The percent recovery was calculated for each check standard submitted. All results fall within the target bias limit of ±10% recovery. The average percent recovery for each concentration is listed in Table 4.

Lab bias was further evaluated using samples spiked with higher concentrations. A spike is performed once for every 20 samples analyzed. Many results affected by matrix interference are qualified by the lab with a "J" qualifier, indicating the result is an estimate. These results are listed in the qualification table in the data appendix (Appendix B).

All of the TP samples collected during the September 24-26, 2001 surveys were qualified as estimates. All samples were manually digested (method SM4500PH) due to a contamination problem with the automated in-line TP analyzer instrument. Samples were digested on the last day of their hold date or afterwards. In addition, samples exceeded sample temperature limit of 4° C while in holding storage.

In all, the TP sample results from these dates seem to show good relative precision, but a negative bias. In most cases, TP results were generally equal to or lower than associated ortho-P results. Ortho-P results for this sample set were deemed excellent.

Accordingly, TP results were rejected for use in comparison with other TP results from other sample dates; however, relative comparison within the qualified sample set was deemed satisfactory (i.e., relative increases or decreases from one station to another were assessed within the qualified data set). Additionally, TP results for some stations were estimated from established TP to ortho-P ratios and used in load determinations and analysis. This was only done if there was a strong linear correlation shown between the two phosphorus partitions at the station in question throughout the study period and if estimated values were within the range of previous values assessed. Figure 3 presents a typical satisfactory correlation at Rocky Ford Creek station RF2.

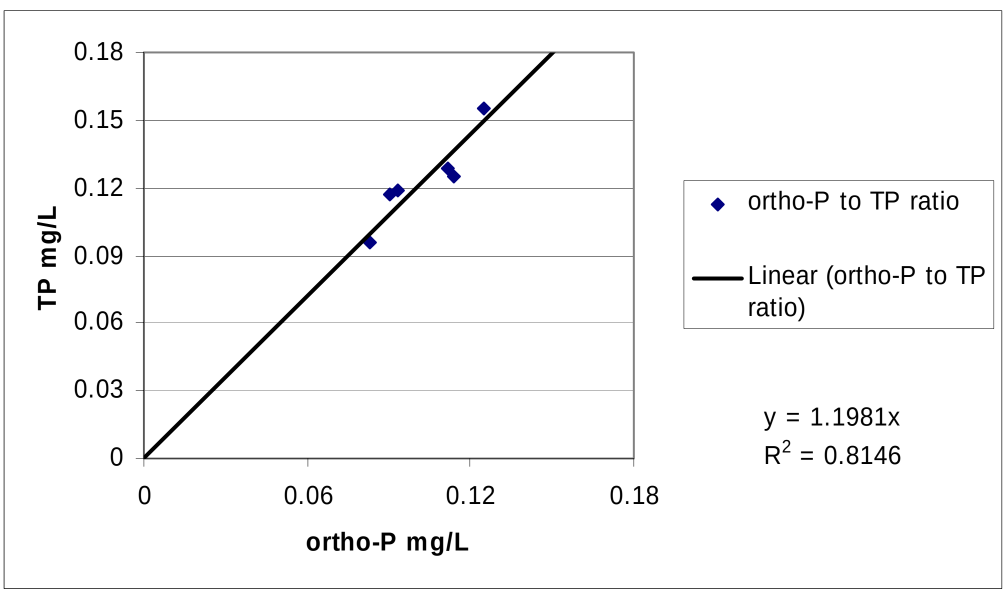


Figure 3. Ortho-P to TP ratio correlation from Rocky Ford Creek station RF2.

Conclusion

The QA and QC review suggest that the Ecology data are of good quality and are properly qualified.

Water Quality Evaluation

1. Rocky Ford Creek

Rocky Ford Creek is one of two natural tributaries to Moses Lake. It is unique as a tributary because of its small watershed size (104 km^2) and yet relatively large mean annual flow. Rocky Ford Creek originates as a series of springs at the Troutlodge 1 fish hatchery and then flows south from the springs for approximately eight miles, discharging to the north end of the main arm of Moses Lake (Figure 4). The Troutlodge 2 hatchery also uses Rocky Ford Creek about a mile downstream of the headsprings.

Most of the flow at the head of Rocky Ford Creek is diverted through both fish hatcheries. Just above the mouth of the creek is a small detention pond created by a dam built in 1987 to retain phosphorus and prevent carp from entering the creek.

Historical Data Review

Rocky Ford Creek is a Class A surface water that has been listed as violating water quality criteria for temperature, pH, and dissolved oxygen. Cusimano and Ward (1998) conducted a TMDL study in 1997 on Rocky Ford Creek. They concluded that the temperature violations were due to natural conditions and recommended that the creek be delisted for temperature. It was also concluded that the dissolved oxygen and pH violations were most likely due to algal/plant growth and decomposition within the creek and adjacent wetlands.

Cusimano and Ward (1998) noted that setting quantitative nutrient loading limits might not be feasible due to the complex nature of wetland and rooted macrophyte processes; however, they conducted their work during an extreme high-flow year when Rocky Ford Creek was flooding its channel. Cusimano and Ward (1998) also suggested that nutrient allocations for Rocky Ford Creek may need to be established as part of the Moses Lake TMDL study in order to protect the lake water quality.

Carroll et al. (2000) reviewed the historical data on Rocky Ford Creek in context to its nutrient contribution and impact on Moses Lake. The review established that, on the average, Rocky Ford Creek contributes 37% of the annual TP load to Moses Lake.

Hydrology

Rocky Ford Creek has an annual average flow of 78.2 cfs (Cusimano and Ward, 1998). The 90^{th} and 10^{th} percentile flows for Rocky Ford Creek are 94 and 46 cfs, respectively. Figure 5 shows a Weibull distribution probability plot of the annual mean flows for Rocky Ford Creek from 1977 through 2001. The mean flow for the 2000-01 water year was 57 cfs, nearly a 20^{th} percentile flow for the 1977 to 2001 time period. Figure 6 shows box plots of the daily flow records by month. The flows in Rocky Ford Creek are relatively stable (day to day) and most of the time range between 40 and 100 cfs. There is a slight seasonal variation, with higher flows occurring during the latter half of the year (May – Dec).

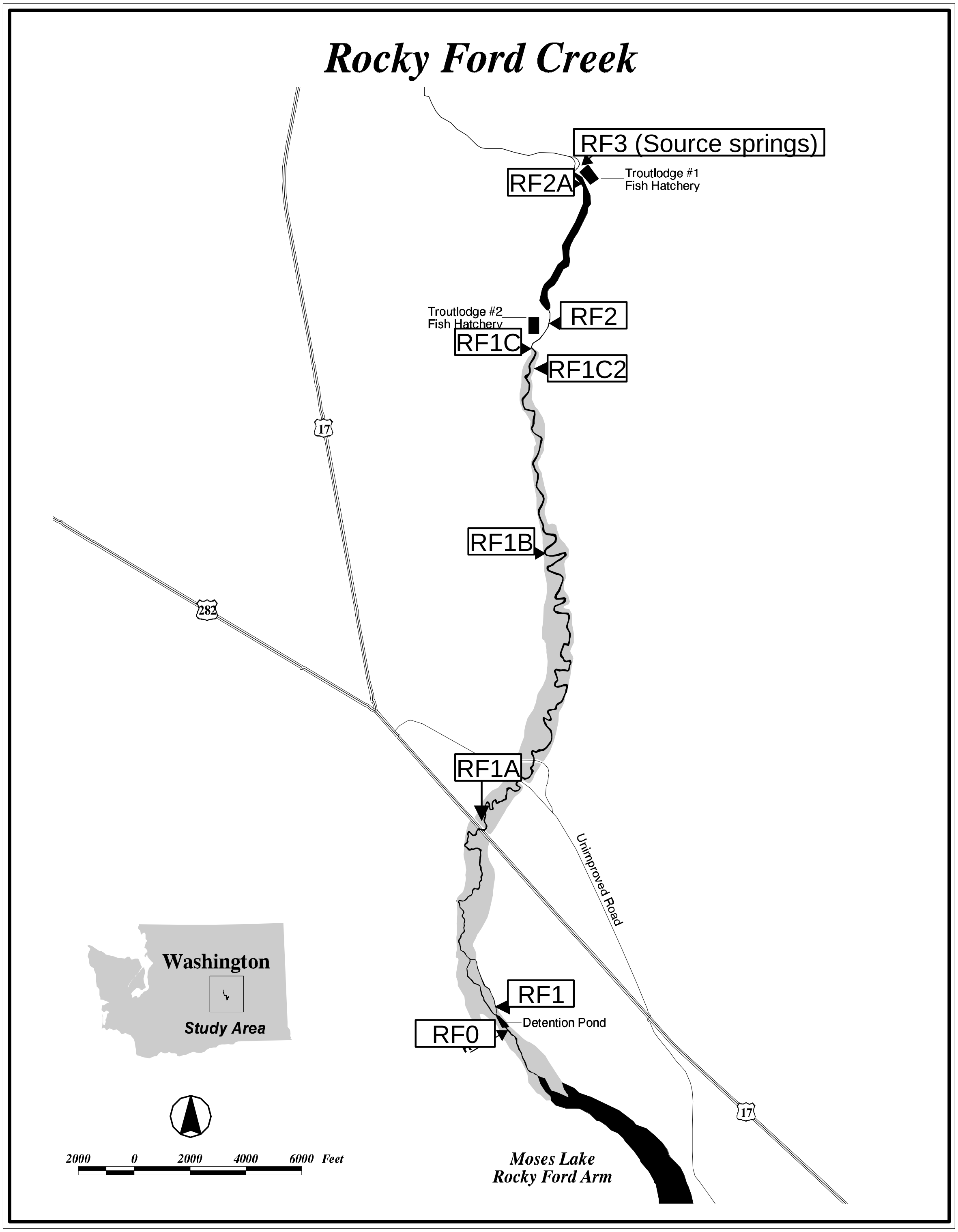


Figure 4. Vicinity map of Rocky Ford Creek and sampling stations.

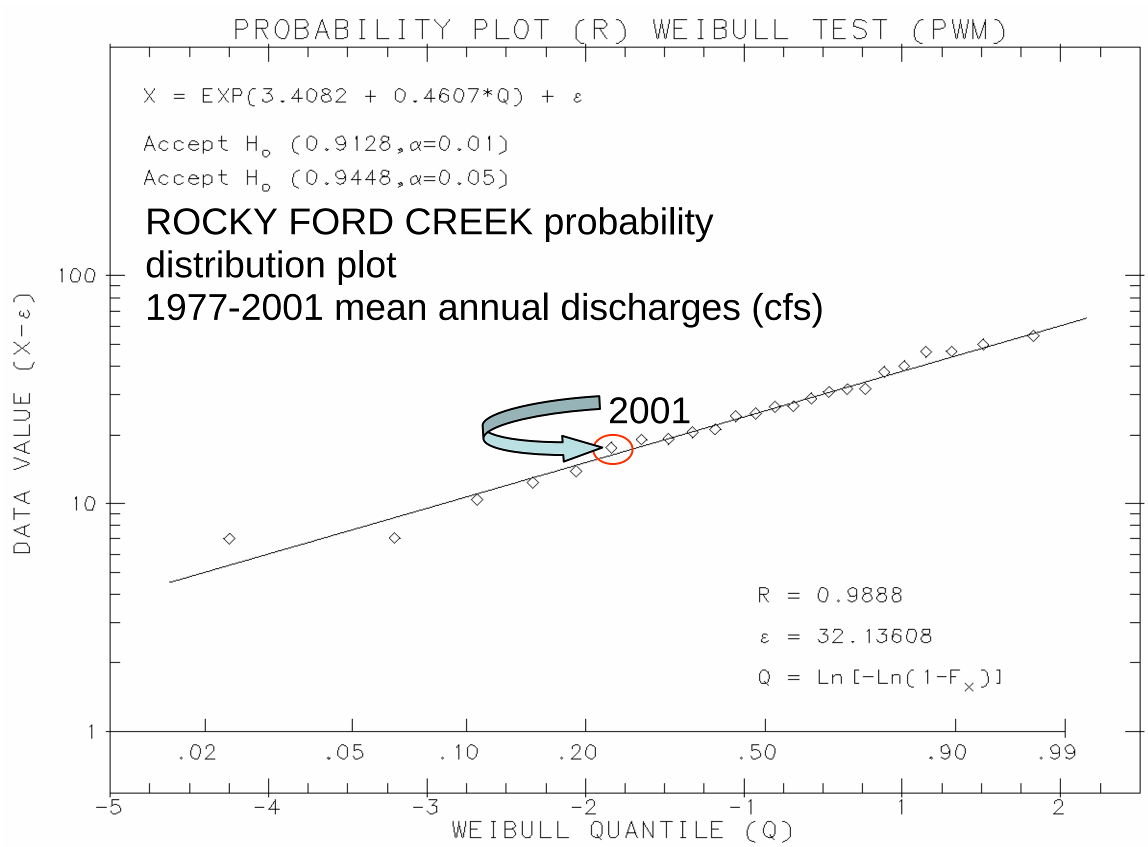


Figure 5. Probability distribution plot of Rocky Ford Creek annual flows (1977 – 2001).

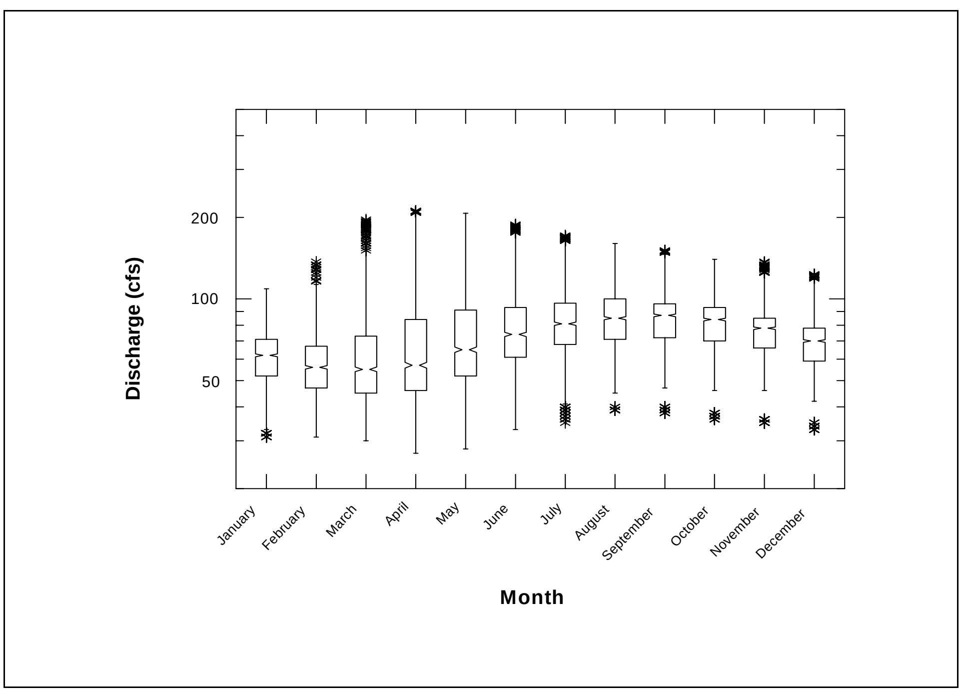


Figure 6. Box plots of daily flow for Rocky Ford Creek from USGS station 12470500 data (1942 – 1991). (See Appendix C for an explanation of box plots.)

USGS operated a gaging station (USGS station 12470500) located about one mile below the springs above Troutlodge 2 from 1942 through September 1991 (located near station RF2 on Figure 4). After 1991 the USGS continued making instantaneous bi-monthly measurements at Highway 17, about four miles downstream of the original gaging station (located near station RF1A on Figure 4). The original gaging station was abandoned because the control for the station was being influenced by the diversion of flow at the Troutlodge 2 hatchery. It was felt that because of the stable nature of the flow on Rocky Ford Creek, the linear interpolation between bi-monthly instantaneous measurements would be sufficient to characterize the daily discharge (Smith, 2001).

USGS never correlated flow at the new USGS gaging site at Highway 17 and the old USGS gaging station; however, Cusimano and Ward (1998) found flow increased approximately 20% (22-26 cfs) from the USGS monitoring station to the lake, suggesting groundwater inflows to Rocky Ford Creek en route to Moses Lake. An increase was also observed in the 2000-01 water year. During a synoptic flow survey conducted on September 25, 2001, measured flow at the old USGS station was 48.7 cfs, while flow at the mouth of Rocky Ford Creek was 81.7 cfs (i.e., a 33 cfs or 68% increase). Most of this increase (24 cfs) occurred between Highway 17 and the mouth of Rocky Ford Creek.

Ecology installed a continuous flow station at the mouth of Rocky Ford Creek (just below the dam) for the 2000-01 study period. Figure 7 presents the flow for this station compared with the USGS interpolated flow data at Highway 17 and the source springs for the 2000-01 water year. There was a seasonal increase of flow from the headsprings to the mouth beginning in May (beginning of irrigation season), and peaking in October (end of irrigation season). This pattern extended from the previous water year as well (i.e., peak in late September 2000) with flows subsiding until there was essentially equal wintertime flow along the entire length of the creek from late December until the beginning of the 2001 irrigation season. Most of the increases in downstream flow took place below the Highway 17 bridge USGS gaging site. This suggests that a locally elevated water table provides a sub-surface seasonal discharge to Rocky Ford Creek, particularly in the last few downstream miles.

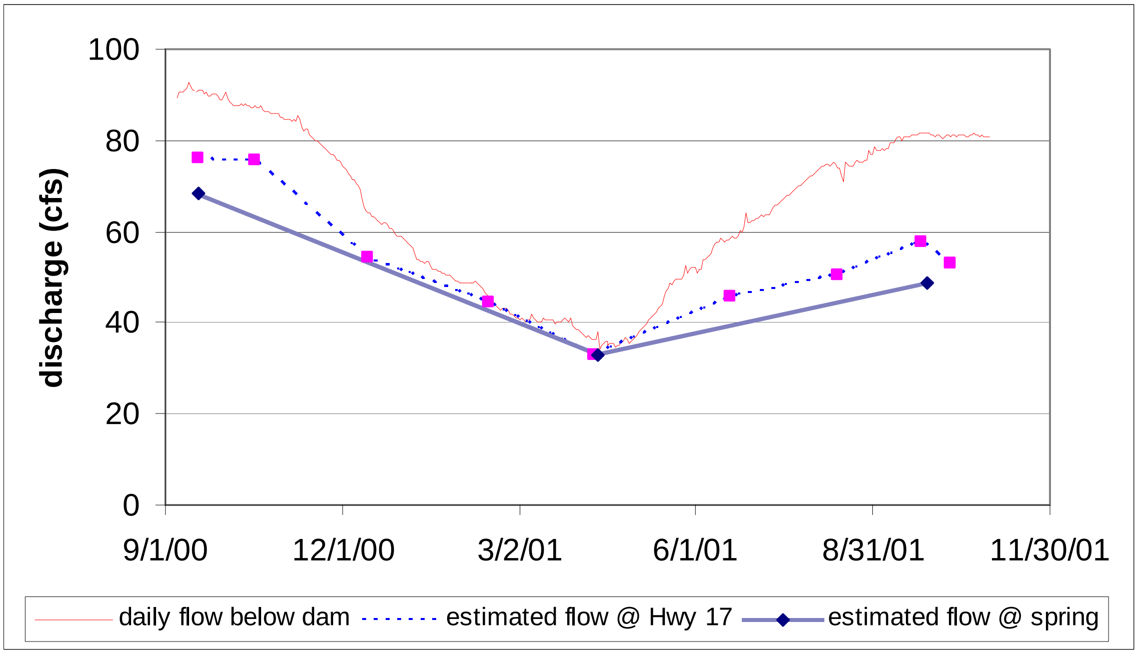


Figure 7. Comparison of study-period flows in Rocky Ford Creek below the dam (near mouth, station RF0), at the Highway 17 bridge, and at the source spring. Estimated flows are made using straight-line interpolation between measured instantaneous flows.

A plot of monthly mean flows in Rocky Ford Creek (Figure 8) from 1942 to 2001 indicates the variability and changing time periods of high versus low discharges that have taken place in Rocky Ford Creek since 1942. Rocky Ford Creek had higher flows in the late 1990s (90th percentile flows from 1997 to 1999), resulting in flooded channels and extended wetlands (Cusimano, 1998). During the late 90s, there was also increased aquatic plant growth (rooted plants) which severely choked the channel, constricted flows, and caused further flooding in the watershed. These conditions did not exist during the 2000-01 water year. The creek remained confined to a distinct channel, and there was no noticeable severe plant-induced choking of the channel, although wetland-like conditions exist more plentifully in the last few miles of Rocky Ford Creek (the creek is multi-channeled and braided below Highway 17).

The most recent evidence (Pitz, 2003) indicates that the Rocky Ford Creek source spring discharge is predominantly derived from shallow groundwater northeast of the springs. The baseline discharge from the spring probably varies with fluctuating regional water table levels, which may reflect the variation in climatic conditions over the region or perhaps greater trends in irrigation patterns. The observed seasonal inflow seen in the lower part of the creek seems to remain fairly constant in either high- or low-flow years (observed flow increases ranged between 22 and 32 cfs for a 20th and 90th percentile annual flow year, respectively), suggesting fairly stable year-to-year groundwater inflows.

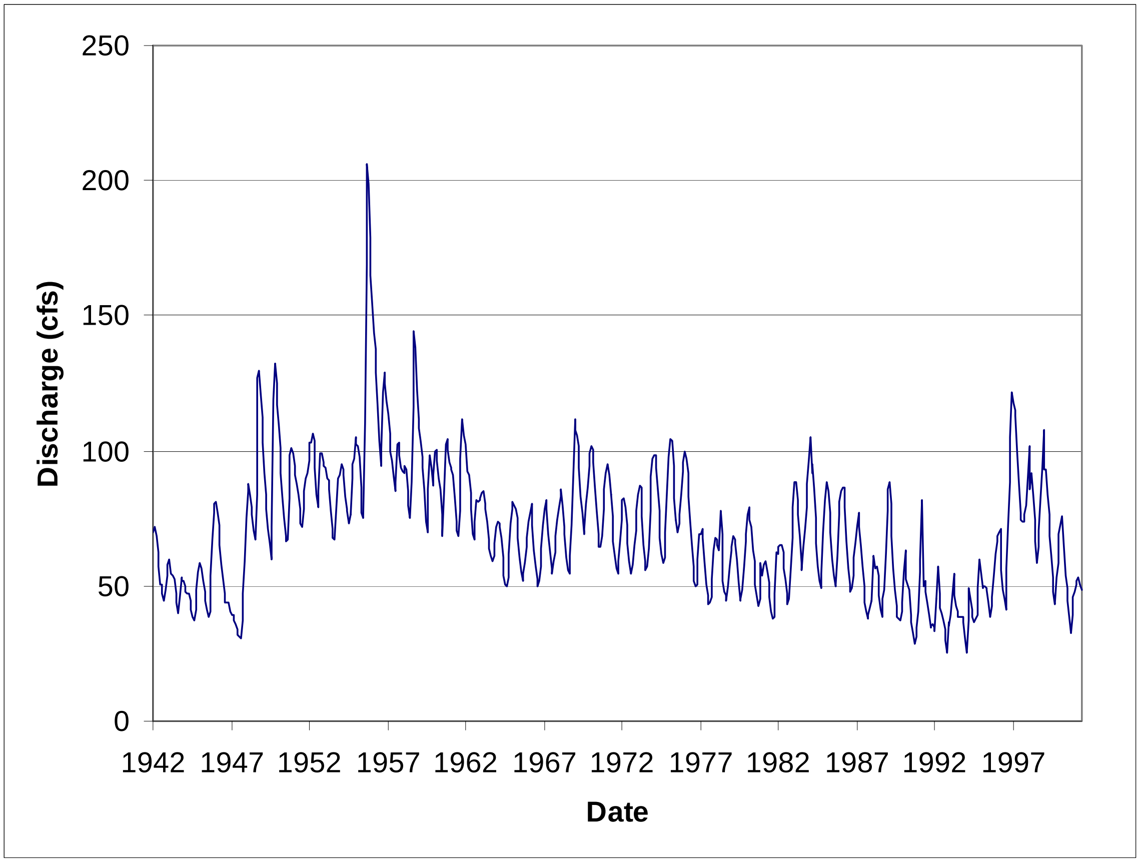


Figure 8. Rocky Ford Creek monthly mean flows from USGS station 12470500 (1941 to 2001). (From October 1991 through October 2001, monthly mean flows were interpolated from bi-monthly USGS data.)

Water Quality Evaluation

2000-01 Monitoring Results

Figure 9 shows all pH, dissolved oxygen, and temperature data collected as instantaneous measurements during the study period. Most sampling and measurements on Rocky Ford Creek were taken before 10AM. Only five instantaneous temperature measurements were measured in excess of the 18° C criterion for Rocky Ford Creek. They were all afternoon measurements made at Highway 17 and the mouth from May to September. For the most part, the predominance of early morning instantaneous measurements missed the peak diurnal temperatures of the afternoon.

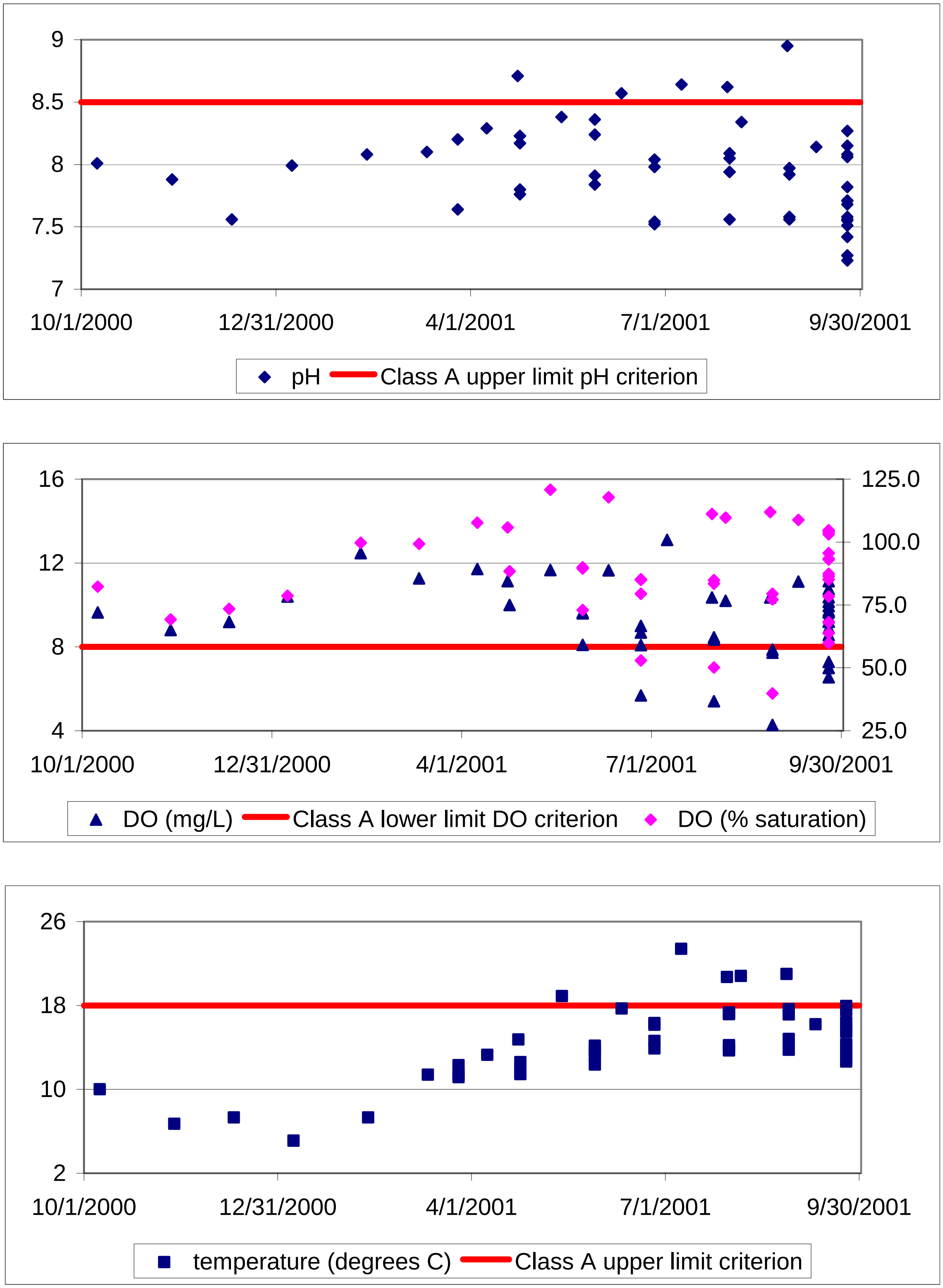


Figure 9. pH, dissolved oxygen, and temperature instantaneous data collected from all sites sampled on Rocky Ford Creek during the study period.

Continuous temperature monitoring at the mouth of Rocky Ford Creek from May to October 2001, presented in Figure 10, illustrates that water temperatures often exceed the 18° C criterion from May through August.

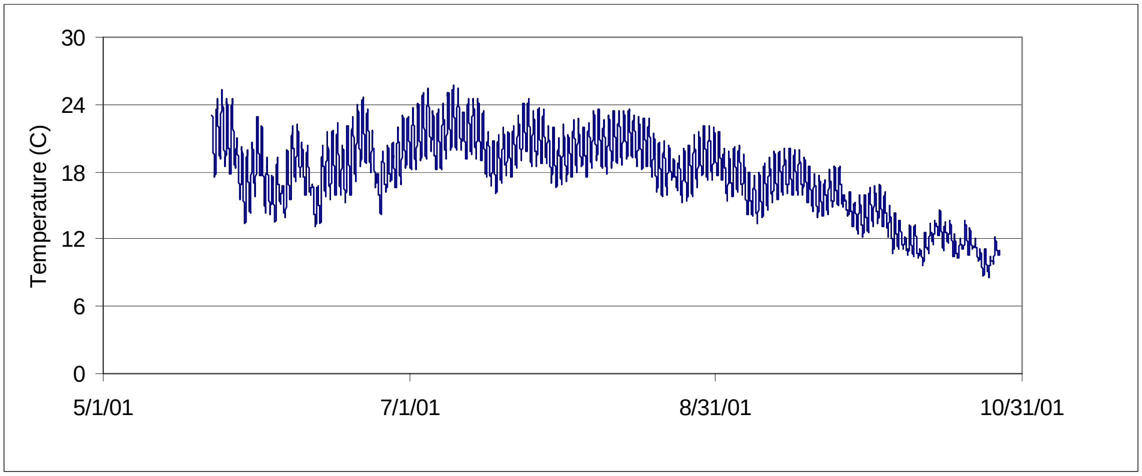


Figure 10. Continuous temperature data collected at the mouth of Rocky Ford Creek.

There were also pH excursions observed at the mouth and Highway 17 sites. Again, these excursions only occurred during the few early to late afternoon observations, and are associated with diurnal pH fluctuations found in Rocky Ford Creek (higher pH occurs in the afternoon due to photosynthesis). For the most part, Rocky Ford Creek is well buffered – total dissolved solids were >240 mg/L and alkalinity was approximately 170 mg/L throughout the study period – which has the effect of dampening pH fluctuations.

Dissolved oxygen (DO) also exhibited a diurnal fluctuation in Rocky Ford Creek, with lower DO concentrations occurring at night and early morning due to plant and algal respiration. In this case, early morning sampling was timely for measuring low DO excursions below the 8.0 mg/L criterion. The site in the downstream reach below the Troutlodge 1 hatchery (station RF2) consistently had very low DO concentrations from the end of June through September during the early hours. The lowest DO concentration measured at this site was 4.3 mg/L (about 35% of saturation) on 8/28/01 at 7:30 in the morning. On this same day, DO excursions were measured at two other sites (RF0 and RF1). On the several occasions it was measured, the headwater springs had a concentration of DO greater than 9.0 mg/L and was consistently about 25% under-saturated.

During a synoptic survey on 9/24/01, station RF2 again violated the DO criterion with a concentration of 7.0 mg/L (56% saturation) at 9:45 AM, but exhibited a net DO production with a concentration of 11.1 mg/L (90% saturation) at 13:45 PM, giving a net DO diurnal range of over 4 mg/L. Cusimano and Ward (1998) reported a DO diurnal range of 3.6 to 9.2 mg/L at the old footbridge above Highway 17 during their August 1997 survey. In 2001, the upper part of Rocky Ford Creek, in particular the reaches immediately below the fish hatcheries, were the most productive reaches of the creek and the most likely to have pH and DO violations.

In general, Rocky Ford Creek exhibited depressed DO concentrations relative to saturation year-round at all sites sampled up and down the creek (average of 76% saturation). Again, most samples were taken in the early morning, but even mid-afternoon DO concentrations were rarely super-saturated. Cusimano and Ward (1998) suggested that the decomposition of wetland plants and algae probably accounts for the year-round depression of DO.

The station below the dam (RF0) was the only station with consistent turbidity violations, though slight, with an average increase of 6.0 NTU over background (background estimated to be 1.0 NTU) from April through August.

Synoptic Survey – September 24, 2001

An intensive synoptic survey of Rocky Ford Creek was conducted on September 24, 2001. This survey occurred during the period of seasonal groundwater inflow in the lower part of the creek. Table 5 summarizes the load contribution or loss (kg/day) at each of the sample stations for nutrients and chlorophyll *a*. Additionally, stations were grouped into categories to analyze the percent contribution of the total load to Moses Lake from various similar sources or sinks within the Rocky Ford Creek watershed.

A summary of findings include:

- The source spring accounted for most (86%) of the nitrate in the creek. There was a net loss of nitrate in the fish hatcheries (-6.5%), probably due to biological uptake associated with photosynthetic activity (i.e., plants and algae) within the hatchery races. Additional sources of nitrate (around 20%) entered Rocky Ford Creek via the seasonal inflows in the lower reaches.

- The fish hatcheries discharged most of the ammonia to the creek. Ammonia is a product of fish metabolism. This readily available nutrient was evidently biologically utilized in the immediate downstream reaches below the fish hatcheries, either as ammonia or the oxidized form of nitrate during nitrification (18% loss). The immediate downstream reaches showed little to no increase in nitrate.

- The fish hatcheries were the major contributor of chlorophyll *a* (i.e., algae) to the creek (38.7%), most likely sloughed from periphyton mats within the hatchery facilities. This is consistent with the uptake of nitrate within the hatchery. There was no (< 1%) chlorophyll in the source springs. The immediate downstream reaches below the fish hatcheries, with their supplies of available ammonia, contributed another nearly 25% of the chlorophyll *a* to the creek.

- The majority of TP and ortho-P originated from the source springs (40% and 49%, respectively). The fish hatcheries contributed 24% of the TP and 17% of the ortho-P, while the immediate downstream reaches below both hatcheries contributed almost another 10% of the TP and ortho-P load. In all, the fish hatcheries and their immediate downstream reaches had a 34% and 26% net contribution of TP and ortho-P, respectively.

Table 5. Summary of results from synoptic survey on Rocky Ford Creek on September 24, 2001

Site	Conductivity			Nitrate			Ammonia			TP			Ortho-P			Chlorophyll a		
	cumulative load *	change in load	% of total load to lak	cumulative load (kg/day)	change in load	% of total load to lak	cumulative load (kg/day)	change in load	% of total load to lak	cumulative load (kg/day)	change in load	% of total load to lak	cumulative load (kg/day)	change in load	% of total load to lak	cumulative load (kg/day)	change in load	% of total load to lak
Spring origin (RF3)	46954		60.3%	240.9		86.1%	1.1		14.6%	8.5		39.7%	10.0		49.4%	0.01		0.9%
Troutlodge I (RF2A)	46824	-129	-0.2%	225.0	-15.9	-5.7%	7.2	6.1	80.3%	11.5	3.0	13.9%	12.2	2.2	10.9%	0.12	0.12	18.2%
Reach below Troutlodge I (RF2)	50637	3812	4.9%	234.1	9.1	3.3%	5.1	-2.1	-28.2%	12.6	1.2	5.4%	13.9	1.6	8.1%	0.28	0.16	24.7%
Troutlodge II (RF1C)	50756	119	0.2%	231.7	-2.4	-0.9%	7.1	2.1	27.5%	14.8	2.1	10.0%	15.1	1.3	6.2%	0.41	0.13	20.5%
Reach below Troutlodge II (RF1C2)	50398	-357	-0.5%	229.9	-1.8	-0.6%	6.8	-0.4	-4.7%	15.3	0.5	2.2%	15.0	-0.1	-0.6%	0.33	-0.08	-12.1%
Reach above Swanson land (RF1B)	50756	357	0.5%	227.0	-3.0	-1.1%	7.9	1.1	14.9%	15.7	0.4	1.9%	15.3	0.3	1.5%	0.41	0.08	12.1%
Reach above Hwy 17 (RF1A)	60028	9272	11.9%	258.8	31.8	11.4%	8.8	0.8	11.1%	18.3	2.6	12.4%	17.8	2.5	12.4%	0.49	0.08	13.1%
Reach above mouth (RF0)	77853	17825	22.9%	279.8	21.1	7.5%	7.6	-1.2	-15.4%	21.4	3.1	14.4%	20.3	2.5	12.2%	0.64	0.14	22.6%
Total load to Moses Lake	77853		100.0%	279.8		100.0%	7.6		100.0%	21.4		100.0%	20.3		100.0%	0.64		100.0%

* Conductivity load calculated as (umhos/cm-1) x (cfs)

Summarized % contribution of total load to Moses Lake (inflows or net biological uptake/release)

	Conductivity	Nitrate	Ammonia	TP	Ortho-P	Chlorophyll a
Spring	60%	86%	15%	40%	49%	1%
Fish hatcheries	0%	-7%	108%	24%	17%	39%
Downstream reaches directly below hatcheries	5%	2%	-18%	10%	9%	25%
Lower creek	35%	19%	-4%	27%	25%	36%

Source Springs and Troutlodge Hatcheries

The source springs originate on the property of the Troutlodge 1 hatchery. The facility is located adjacent to a bluff, from which the springs emerge at the base. Historically the springs emerged to the ground surface, but in past years Troutlodge buried interceptor lines that run parallel to the bluff and intercept the springs. The water is conveyed through the interceptor lines to a number of manifold vaults where the water is directed into the hatchery. Ecology sampled one manifold vault monthly beginning with the April sampling. However, during the synoptic sampling on September 24, 2001, two additional vaults also were sampled.

The synoptic sampling of the three spring manifold vaults revealed variable results (Table 6) leaving the representativeness of any individual spring vault sample in regards to the total source spring inflow contribution unknown to Ecology. Table 7 presents the summary of results from all the spring source samples collected during 2001.

Table 6. Summary of results from Rocky Ford Creek source spring samples taken on September 24, 2001.

Parameter	Mean	Minimum	Maximum
TP (ug/L)	Rejected data	----	----
Ortho-P (ug/L)	91	66	109
Total nitrogen (mg/L)	3.40	3.04	3.95
NO23-N (mg/L)	2.17	2.07	2.53
Conductivity (umhos/cm)	424	401	436

Table 7. Summary of results from Rocky Ford Creek source spring samples, April through September 2001.

Parameter	Mean	Minimum	Maximum	90^{th} percentile
TP (ug/L)	103	75	119	125
Ortho-P (ug/L)	82	65	109	103
Total nitrogen (mg/L)	3.03	2.51	3.95	3.74
NO23-N (mg/L)	2.57	1.92	3.02	2.98
Conductivity (umhos/cm)	529	401	705	705
Chloride (mg/L)	6.73	3.35	11.1	11.22

The water quality influence of Troutlodge 1 on Rocky Ford Creek was assessed from April through September 2001. Sampling was affected because of access issues on site of the hatchery grounds (i.e., direct hatchery effluent), so samples were taken just downstream of the hatchery facility in a zone assumed to be completely mixed. Troutlodge 2 performance was assumed to equal the performance of Troutlodge 1.

The Troutlodge 1 hatchery is situated so that most, if not all, of the flow from the source springs is directed through the facility and then emerges into the creek channel directly below the facility (station RF2A). Samples were collected from this site directly below the facility for the synoptic survey on September 24, 2001. Otherwise, all other samples from April through September 2001 were collected further downstream at the old USGS gaging station (RF2).

The change in nutrient loading after source spring water passed through the Troutlodge 1 hatchery was assessed by comparing source spring and downstream parameter loads and is summarized in Table 8 along with data collected by Cusimano and Ward (1998). In general, the hatchery increased TP, ortho-P, and ammonia loads, while reducing the total nitrogen and nitrate loads. While ammonia concentrations were below detection limits in the spring water, ammonia loads increased sharply from hatchery contributions, though un-ionized ammonia was not present in toxic quantities.

Table 8. Change in Rocky Ford Creek source spring nutrient loads passing through the Troutlodge 1 hatchery.

Change in Load	Nitrate		Ammonia		TP		Ortho-P	
	kg/day	%	kg/day	%	kg/day	%	kg/day	%
During 9/24/01 synoptic survey	-15.9	-7.1	6.1	650	3.0	25.9	2.2	18.1
During 8/20/97 survey (Cusimano and Ward, 1998)	-22.6	-1.9	19.5	660	11.5	52.9	11.5	52.6

Troutlodge 1 produced and discharged less TP and ortho-P in 2001 than in 1997. The 2001 production level (based on feed use) was close to half of that reported for 1997. The percent changes from upstream TP loads were also reduced for both years. If the percent increase of TP in 2001 were normalized to 1997 production levels, the hatchery would have contributed a higher percentage of TP to the creek than in 1997.

Cusimano and Ward (1998) warned that the percent contribution of TP to Rocky Ford Creek, and ultimately to Moses Lake, from the hatcheries could become substantially higher due to changes in the creek flow and fish hatchery production levels. Troutlodge estimated that the hatcheries had a combined usage of approximately 1.25 million pounds of feed in the 2001 calendar year, with fairly stable month-to-month usage (Parsons, 2002). In addition, Troutlodge indicated that they expected increased production from both hatcheries in the future. The 2001 level was less than the 1997 feed level reported by Cusimano and Ward (1998) and only 25% of the maximum permitted feed level of over 5 million pounds.

The cumulative effect of the Troutlodge 1 hatchery effluent and immediate downstream biological activity on nutrient loads were assessed from April through September 2001 by comparing source spring loads with downstream parameter loads at station RF2. A summary of these monthly results reflect the same trend of increasing TP, ortho-P, and ammonia, with decreasing total nitrogen and nitrate-N (Table 9).

Table 9. Percent change in source spring nutrient loads passing through Troutlodge 1 hatchery.*

Month of 2001 sampling	Total Nitrogen (%)	Nitrate (%)	Ammonia (%)	TP (%)	Ortho-P (%)
April	-29.5	-37.6	1000	19.4	25.0
May	-33.7	-36.0	770	28.0	25.8
June	-23.8	-28.6	1140	7.2	43.1
July	-45.4	-34.6	1200	8.4	13.1
August	-29.4	-36.1	990	13.6	12.9
September	-38.6	-30.6	480.0	30.2	16.8
Mean, April – September	-33.4	-33.9	930.0	17.8	22.8

* Includes immediate downstream reach measured at station RF2

Kendra (1989) summarized the work of numerous investigators who documented water quality degradation downstream of fish hatcheries, including increased downstream algal and periphyton growth and productivity. Three of seven sites (RF1B, RF1C, RF2) exhibited low dissolved oxygen excursions during the synoptic survey on September 24, 2001; all three sites were in downstream reaches directly below the hatcheries. These excursions occurred in the morning hours, but not in the afternoon, reflecting the dissolved oxygen dynamics of plant and algal photosynthesis and respiration.

According to the Troutlodge facilities manager, both hatcheries pump cleaning wastewater and solids to off-line settling ponds. The settling ponds have no direct return to Rocky Ford Creek, but seep to groundwater (Witt, 2002). The nutrient increases observed from the hatchery were in the dissolved phase (i.e., ortho-P, ammonia) and were in the normal process water running through the hatchery.

Between the work compiled by Cusimano and Ward (1998) and this study, the TP contribution from the Troutlodge hatcheries during a high-flow year and a low-flow year are represented. However, the production levels were below normal in 1997 and apparently even lower in 2001, so the effect of increasing production levels at the hatcheries is still unclear, although it warrants consideration when determining potential TP loading to Rocky Ford Creek and ultimately to Moses Lake.

Seasonal Inflows

Water samples were collected once per month from Rocky Ford Creek at Highway 17 and below the dam; however, they were not collected on the same day (there was a two-week interval between collection times). Constituent loads were calculated for Rocky Ford Creek at Highway 17 and below the dam (station RF0). Figure 11 shows the increase in conductivity load occurring between the two sites during 2001. Again, the seasonal increase in conductivity load follows the same timing pattern as the seasonal increase in flow. Conductivity was considered to be a conservative tracer in this instance and confirms the increase in flow between the two sites. An average conductivity of 350 umhos/cm for the inflowing groundwater was back-calculated from the increase in conductivity load between the two sites during the four-month period of June through September. This compares well with the average conductivity (323 umhos/cm) measured in groundwater sampled from a mini-piezometer near this area during the same period (Pitz, 2003).

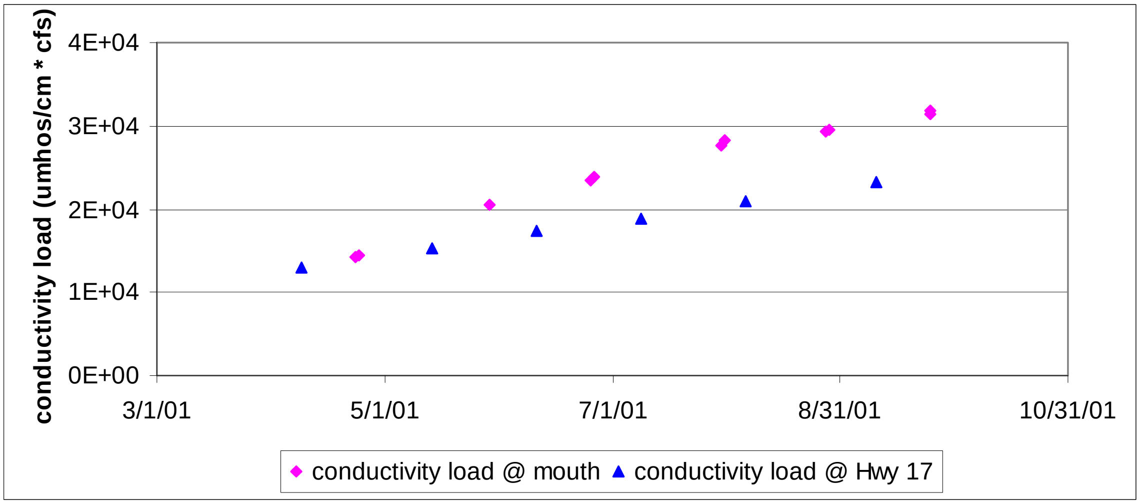
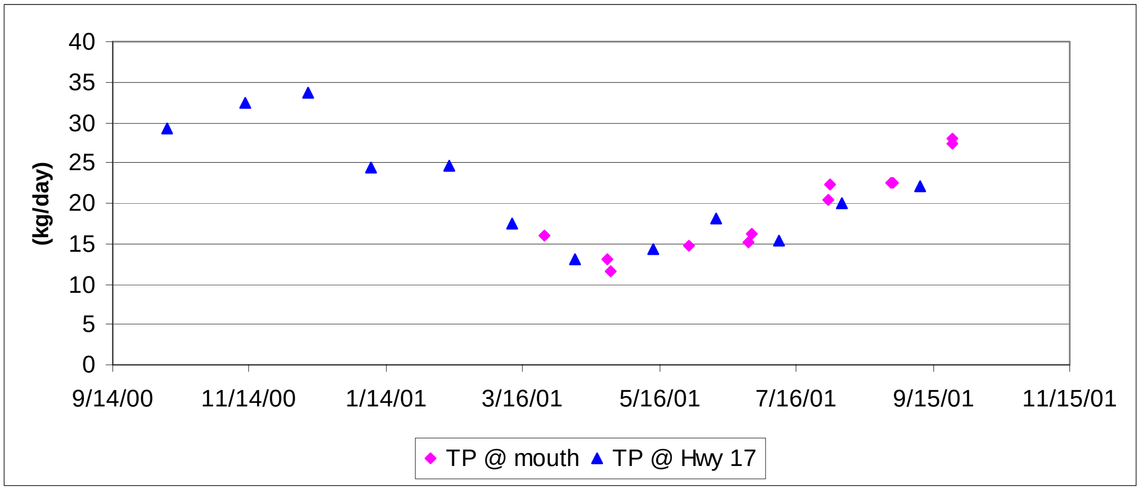


Figure 11. Comparison of conductivity loads in Rocky Ford Creek near the mouth of the creek (station RF0) and at the Highway 17 bridge.

Figure 12 show the calculated TP and ortho-P loads for Rocky Ford Creek at Highway 17 and its mouth. While one might expect to see increases in the loads of other constituents, similar to the conductivity load increase, phosphorus showed no increase in loads for the whole growing season. Integrating the loads from March through September indicated there was no apparent increase in phosphorus loads, though shorter integrated periods indicated compensating gain and loss periods for TP and ortho-P (Table 10). Differences in loads were often small compared to variability observed, except for the conductivity.

Table 10. Comparison of differences of integrated loads by parameter at two sites (Hwy 17 and RF0) on Rocky Ford Creek and associated variability for each parameter.

Parameter	% difference of integrated loads between Rocky Ford Creek at Hwy 17 and near mouth (RF0)			Pooled coefficient of variation for paired field duplicates at station RF0
	March thru June	July thru September	March thru September	
Total Phosphorus	-6.4%	10.4%	2.9%	9.7% n=5
Ortho-P	-9.6%	8.4%	0.5%	2.9% n=2
Total Nitrogen	-5.5%	1.9%	-1.6%	4.2% n=5
Nitrate-N	2.3%	2.3%	2.1%	3.8% n=5
Conductivity	17.5%	24.7%	21.4%	2.5% n=5



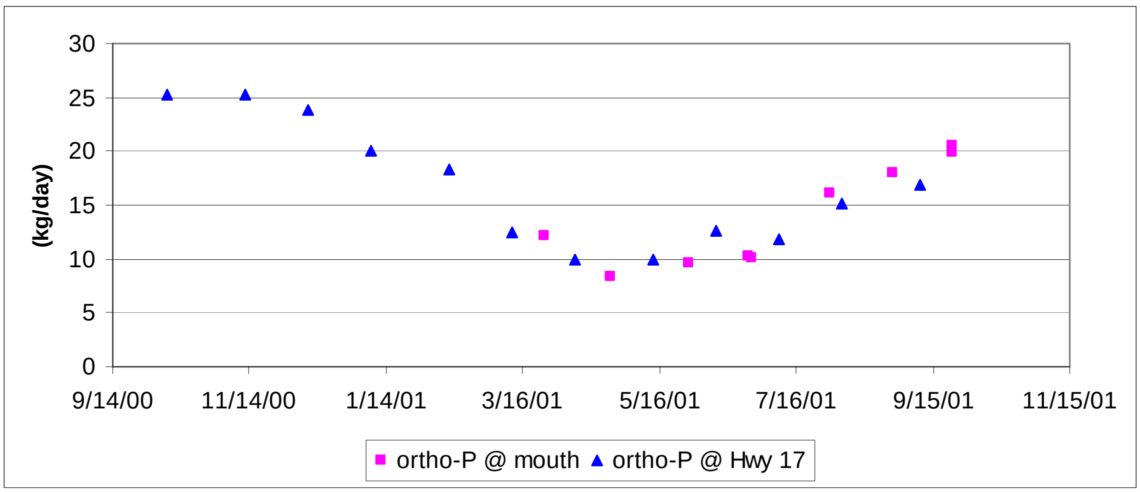


Figure 12. Comparison of TP and ortho-P loads in Rocky Ford Creek near the mouth of the creek (station RF0) and at the Highway 17 bridge.

Detention Pond

The designed detention pond near the mouth and above station RF0 was sampled to assess its removal of nutrients. The detention pond structure was built near the mouth of Rocky Ford Creek in 1987. It was designed to trap nutrients associated with suspended sediments entering the pond. Sediment settling and plant uptake within the detention pond was hoped to assist with nutrient removal from Rocky Ford Creek. An additional benefit of the dam for the detention pond was to keep carp from moving upstream from Moses Lake into Rocky Ford Creek. The state Department of Wildlife attempted to eradicate the remaining carp in Rocky Ford Creek following construction of the dam in 1987, but carp have moved back into the creek since, either by incomplete earlier eradication or upstream passage over the dam when it was vandalized in the mid-90s.

The detention pond has not shown any phosphorus reduction in the past. Various reports (Welch et al., 1989; Cusimano and Ward, 1998) have shown there has not been any significant difference in TP concentrations between samples taken directly above and below the detention pond. The detention pond's ineffective nutrient removal was further corroborated by data collected for this current study. An assumption of this present analysis is that the flow entering and exiting the detention pond are equal. This assumption is reasonable in that the detention pond is only about 400 meters long (about a quarter mile) which is a short distance for substantial sub-surface recharge. Additionally, the head level of the water is artificially high in this location due to the pond, further reducing the likelihood of substantial sub-surface recharge within the short pond reach due to the reduced vertical hydraulic gradients.

Figure 13 shows the concentrations of TP and ortho-P forms upstream and downstream of the detention pond. A paired t-test was done to evaluate if the differences in upstream and downstream concentrations were significantly different from zero. There were no significant differences ($\alpha = 0.05$) between the upstream and downstream sites for TP, total nitrogen, and ortho-P during the growing season of 2001. However, nitrate-N slightly decreased, and ammonia-N slightly increased, in Rocky Ford Creek as it passed through the detention pond. Cusimano and Ward (1998) showed a decrease in nitrate during their study year as well. The percentage of ortho-P to TP averaged 75% upstream of the detention pond and 72% downstream of the detention pond throughout the growing season. During the same period, the percentage of nitrate-nitrite to total nitrogen averaged 89% upstream of the detention pond and 87% downstream of the detention pond.

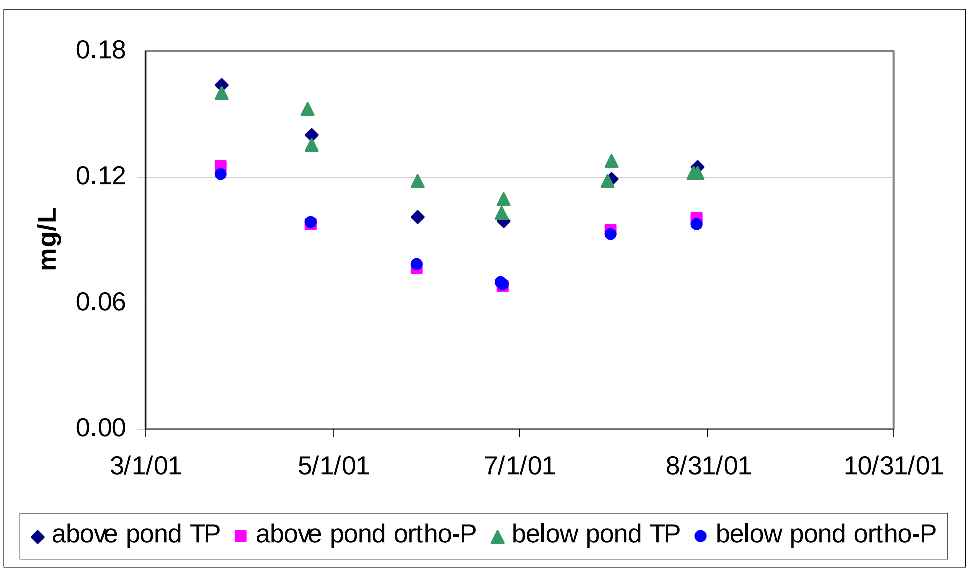


Figure 13. Comparison of phosphorus forms above and below the detention pond near Rocky Ford Creek.

The detention pond is small and is silted in, so the residence time for the water is short. The pond basically behaves as a flow-through system and does not assist in the removal of phosphorus loads to Moses Lake as intended. Still, when the dam is intact, it acts as an effective barrier to upstream migration of undesirable fish from Moses Lake.

The dam was the object of vandalism in the mid 90s and has been a source of contention among local landowners. Contrary to some beliefs, the retention of water in the detention pond has no effect on upstream (above Highway 17) hydraulics, flooding, or weed growth. Carp have repopulated Rocky Ford Creek and, though the state Department of Fish and Wildlife is considering further rehabilitation measures, the carp probably present no serious detriment to other fisheries in Rocky Ford Creek at this time (Korth, 2002). The carp may in fact help reduce the aquatic weed growth which has had a greater impact on the fisheries through productivity-related dissolved oxygen depletion, than a direct adverse effect on trout *per se*. Trout fish kills have taken place in years with high aquatic weed growth in Rocky Ford Creek.

Phosphorus Loading to Moses Lake

Daily nutrient loads from Rocky Ford Creek were developed from a seasonal and flow-weighted regression using continuous flow data and monthly to bi-weekly sampling data. Since concentration data were collected only from the mouth (station RF0) throughout the latter part of the study (mid-March through September 2001), concentration data collected at Highway 17 was used for October 2000 through March 2001. Again, flows at both sites were relatively equal throughout the winter, and nutrient loads were assumed to be relatively the same between the two sites during the non-growing season. The regression had a root mean squared error (RMSE) of 1.5 kg/day with a coefficient of variation of 7.4% (n= 20).

The October 2000 through September 2001 (study period) monthly TP loads are compared with historical (1960-89) mean and 90th percentile loads in Figure 14. Seasonal variation was present, with the highest TP loads occurring at the end of 2000 and the lowest TP loads occurring during the summer months of 2001. The TP loads were 62% of the average April through September loads, reflecting the less than average flow in Rocky Ford Creek for the study period (the study period had about a lower 20th percentile flow). In addition, there was also seasonal variation in phosphorus concentrations (Figure 15). Concentrations were higher than average in the winter months and lower than average in the summer months. The ratio of ortho-P to TP for the study period was 74.5% (standard deviation of 6.2%; n=13) for the year, with slightly higher ratios occurring in the winter months.

Based on data collected in 1997 (sampled in August and November), the fish hatcheries on Rocky Ford Creek were estimated to contribute an average of 21% of the TP load to the creek, and ultimately 10% of the TP load to Moses Lake (Cusimano and Ward, 1998). During 2001, the fish hatcheries were estimated to contribute 14% of the TP load from Rocky Ford Creek to Moses Lake on average from May to September (Figure 16). Cusimano and Ward (1998) indicated that the fish hatcheries' percent contributions to the Rocky Ford Creek nutrient load could be substantially higher in years with lower creek flows and higher fish hatchery production levels. Fish hatchery contributions could approach 75% of the nutrient load to Moses Lake in extreme cases.

The annual TP load from Rocky Ford Creek to Moses Lake was 7,930 kg for October 2000 through September 2001 (study period), with an average annual flow rate of 57 cfs and an average TP concentration equal to155 ug/L. When the study period's annual TP load and average flow is plotted with the same data from other studies spanning the last 40 years, the consistent nature of the TP loading from Rocky Ford Creek is evident (Figure 17).

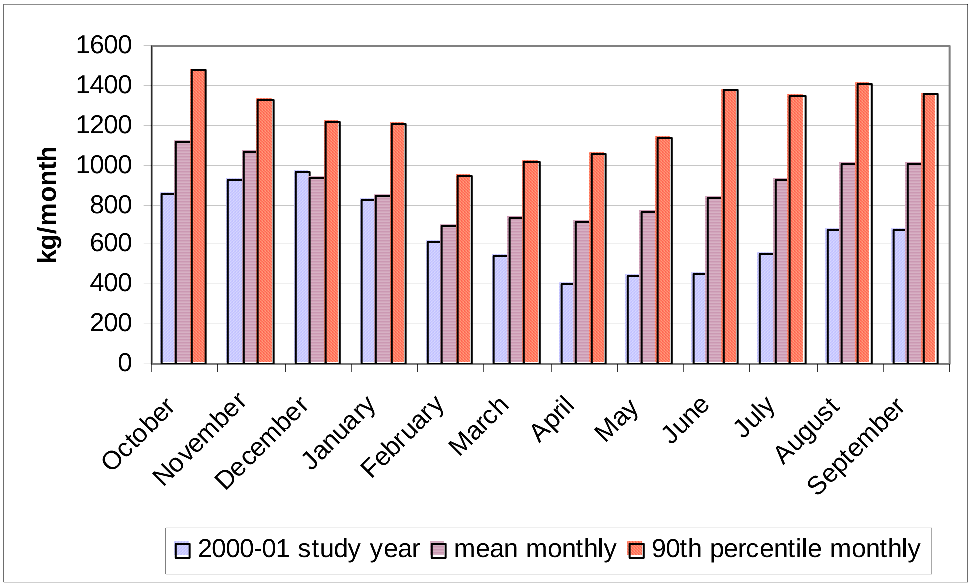


Figure 14. Study-period TP loads from Rocky Ford Creek to Moses Lake compared to historical mean and 90th percentile loads (means and 90th percentiles from Carroll et al., 2000).

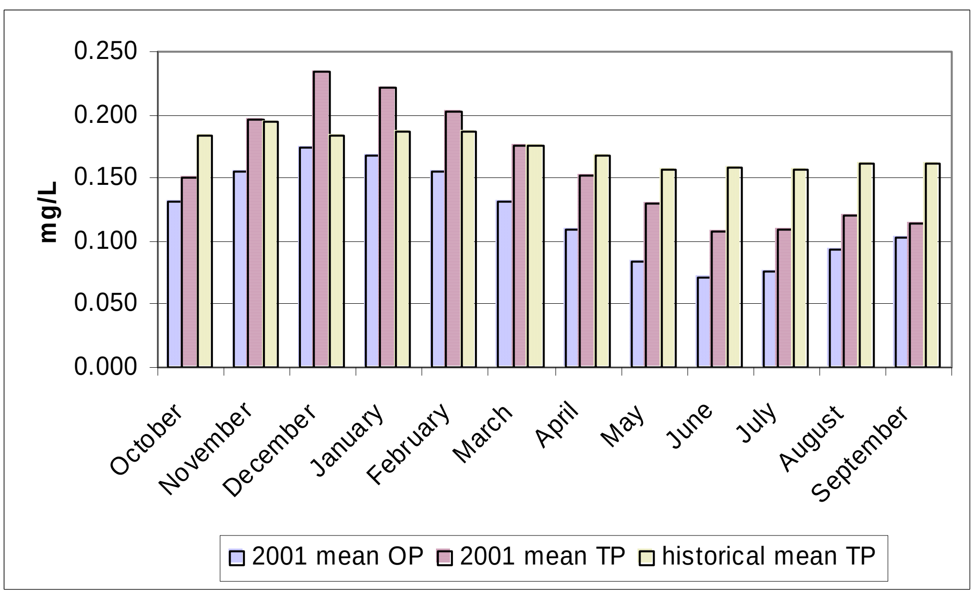


Figure 15. Study-period ortho-P and TP concentrations at the mouth of Rocky Ford Creek compared to historical TP concentrations (historical means from Carroll et al., 2000).

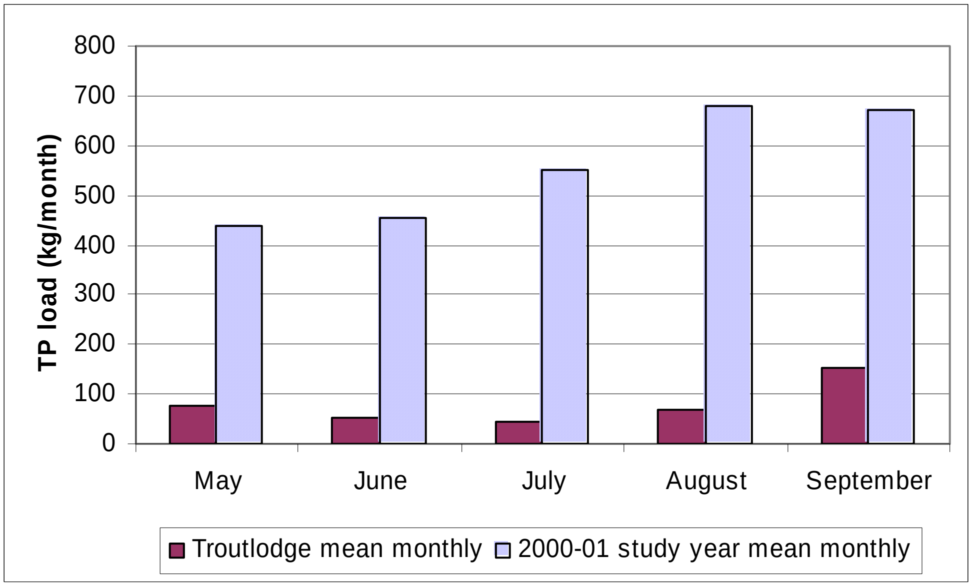


Figure 16. Rocky Ford Creek TP load to Moses Lake compared to apportioned load attributable to Troutlodge fish hatcheries, May through September 2001.

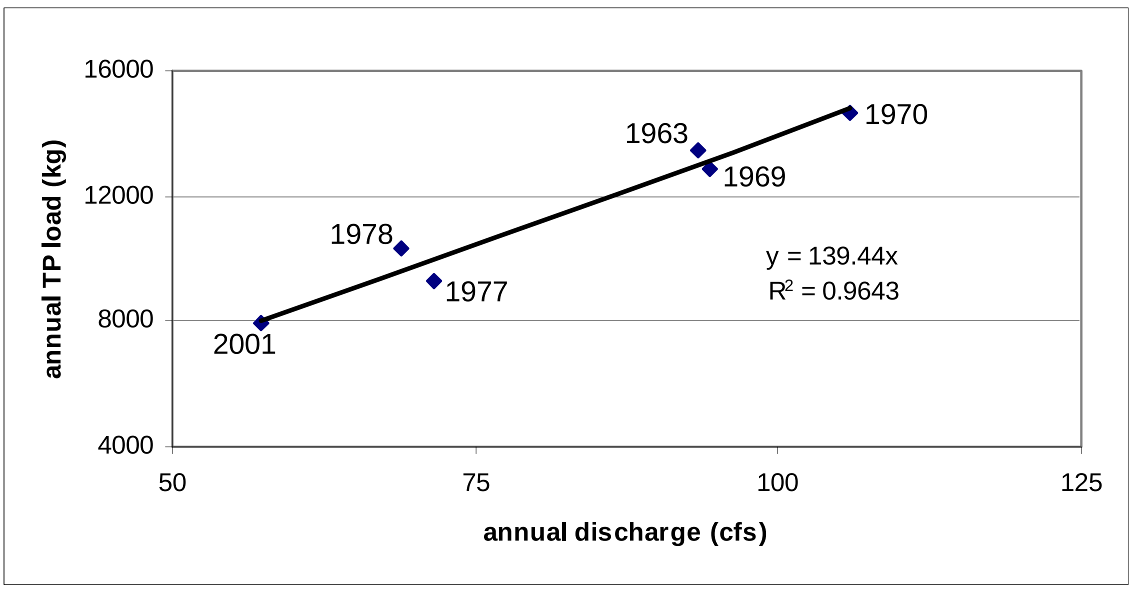


Figure 17. Plot of 2000-01 study-period and historical annual discharges from Rocky Ford Creek and related estimated TP loads (from various sources; see Carroll et al. (2000) for historical review).

The estimated annual TP loads have been a linear function of the flow (RMSE = 454 kg; CV= 4%) for the last 40 years. This constant relation of TP load with flow suggests that contribution from the hatcheries or other sources have not changed in the last 40 years. The average annual TP concentration derived from this relationship is 156 ug /L of TP.

Because of the consistently moderate flow and elevated nutrient levels, Rocky Ford Creek contributes substantially to the annual nutrient loading to Moses Lake. Nutrient concentrations have remained high in Rocky Ford Creek since water quality monitoring began in the early 1960s, despite some attempts at nutrient reduction (i.e., the detention pond). The origin of the particularly high phosphorus levels in the source springs has been the subject of speculation and inquiry. Pitz (2003) states that the area background ortho-P concentration for groundwater in the surficial aquifer system is less than 50 ug/L.

2. Crab Creek

Historical Data Review

Crab Creek is the more variable natural tributary to Moses Lake compared to Rocky Ford Creek. Crab Creek is designated as Class B surface water even though it is a feeder tributary to Moses Lake. It has been listed as violating water quality criterion for pH. Carroll et al. (2000) reviewed the historical data on Crab Creek in the context of its nutrient contribution to and impact on Moses Lake. The review established that, on the average, Crab Creek contributes 13% of the TP load to Moses Lake, although there is a large variability associated with this contribution. Flow regimes during different study years have resulted in Crab Creek contributing from 11% (Sylvester and Oglesby, 1964) to 49% (Welch et al., 1973) of the TP load to Moses Lake.

Hydrology

Although its watershed area is 2040 mi^2, Crab Creek has a lower annual mean flow to Moses Lake than Rocky Ford Creek. During the summer, much of Crab Creek flow goes underground. Prior to the beginning of the Columbia Basin Irrigation Project (CBIP) in 1952, Crab Creek surface flow was negligible except during periods of heavy winter/spring runoff. A USGS discharge monitoring station (USGS station 12467000), located 3.2 miles upstream of Moses Lake, provides a long-term flow record for Crab Creek (located near station CC1 on Figure 1). Since 1960, the mean annual flow has been 44.5 cfs. However, Crab Creek essentially has two flow regimes (winter and summer) and each warrants examination and separate consideration as to the impact it has on the water quality of Moses Lake.

Figure 18 shows box plots of Crab Creek daily flow by month. There are two distinct seasons to Crab Creek flow: highly variable (unpredictable) flow beginning in January and running through April, and relatively stable (predictable) flow from May to December. High flows can occur from January through April and, in some years, large winter/spring runoff events have produced flows greater than the entire annual flow of Rocky Ford Creek. Figure 19 shows discharge for Crab Creek from 1960 to the present. Large winter/spring runoffs (>500cfs) have occurred during 40% of the last 40 years, with four large events occurring in four successive years in the late 1990s.

During the October 2000 through September 2001 study period, there was not a winter/spring runoff event. In fact, the 2000-01 water year flow was the lowest since 1977 (Figure 20). There was discontinuous flow below Brook Lake the entire year, until a gradual accumulation of sub-surface seepage (and possible irrigation returns) around the Gloyds Seeps area again provided for a small surface flow into Moses Lake. Summer time flows into Moses Lake from Crab Creek initiate from these sub-surface (or return) flows near Gloyd Seeps.

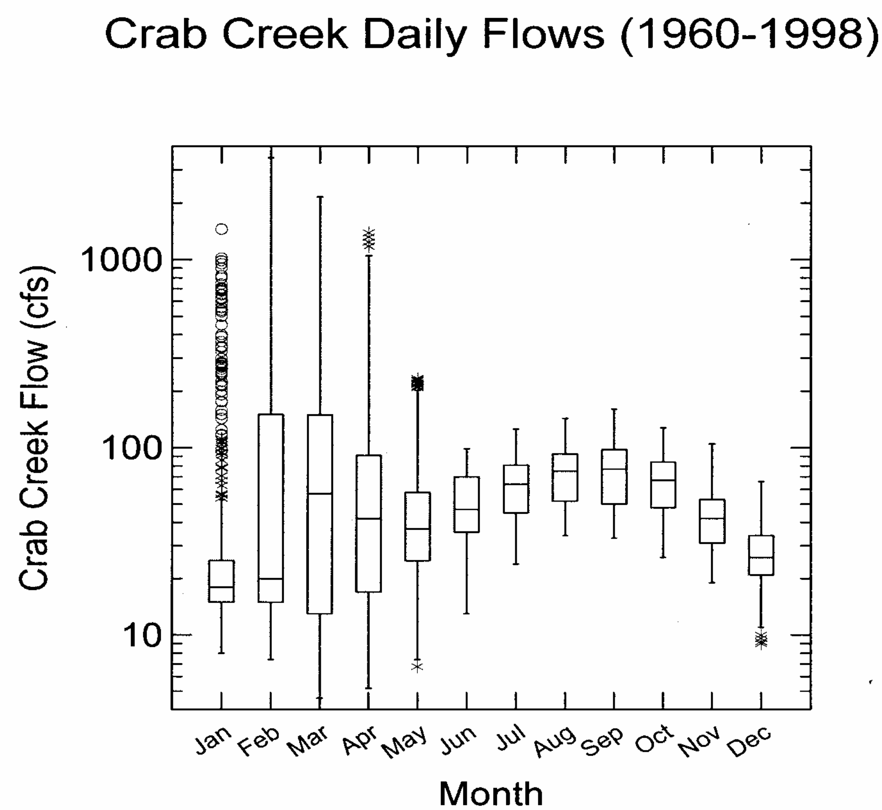


Figure 18. Box plots of daily flows for Crab Creek from USGS station 12467000 data from 1960 to 1998. (See Appendix C for an explanation of box plots.)

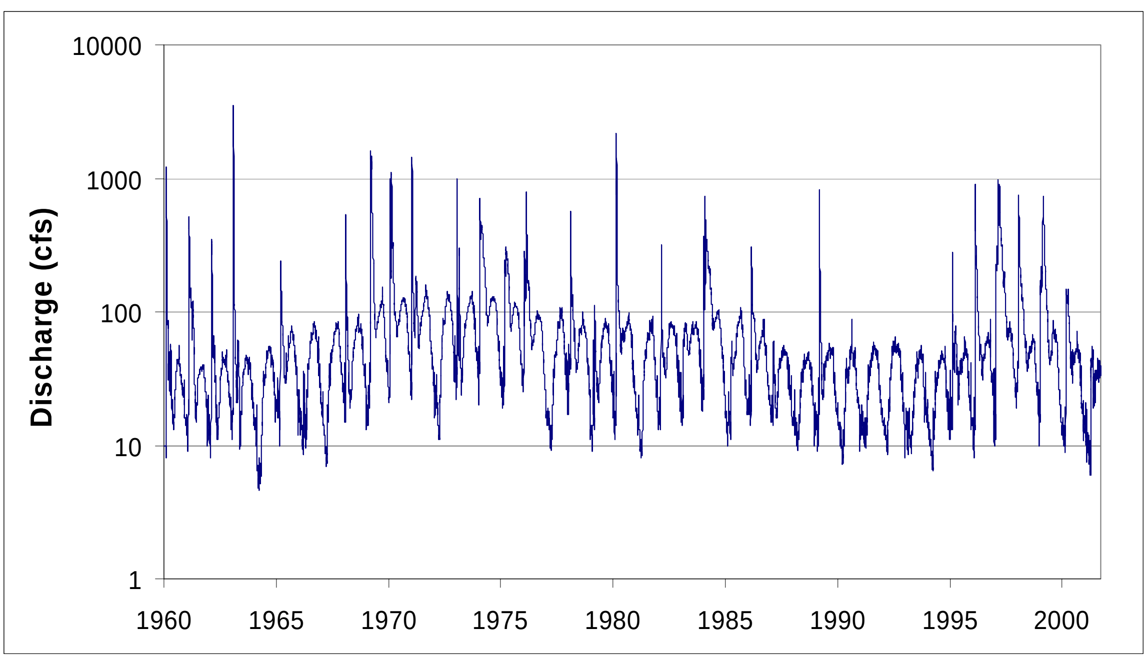


Figure 19. Crab Creek above Moses Lake daily flows from USGS station 12467000 data from 1960 to October 2001.

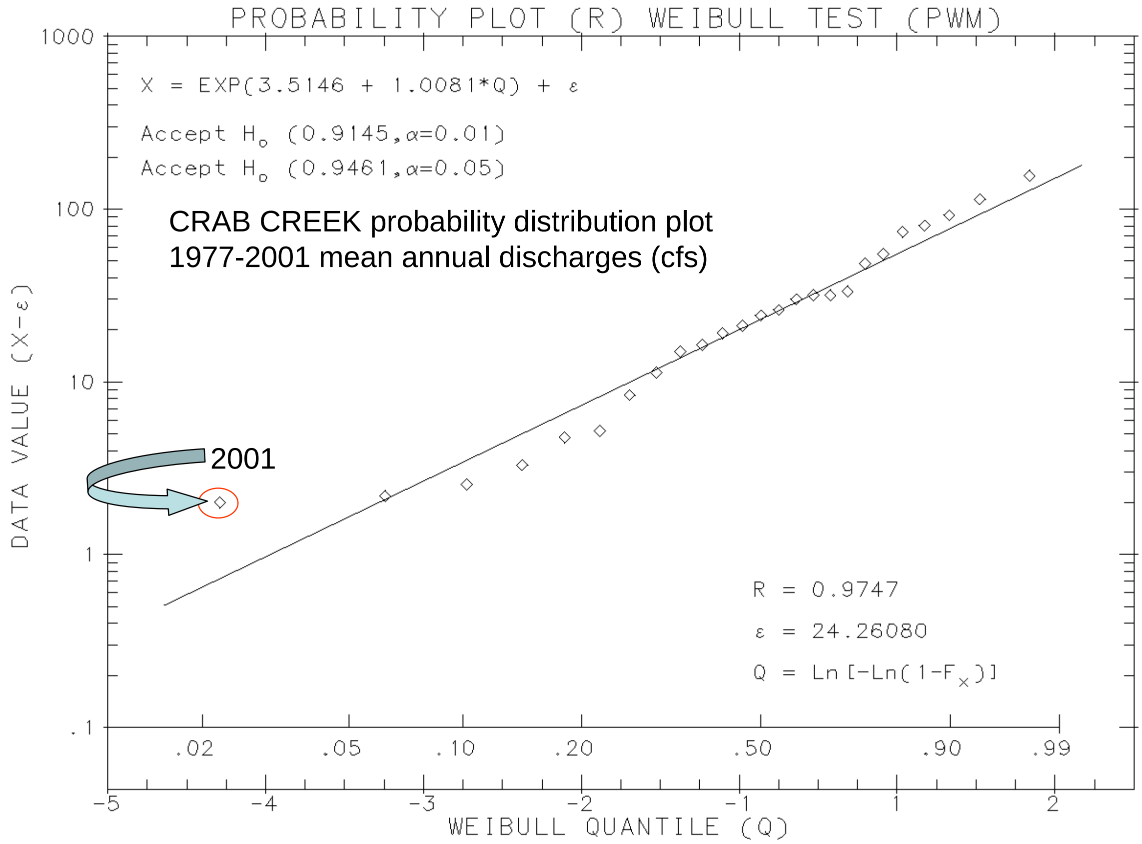


Figure 20. Probability distribution plot of mean annual discharges for Crab Creek from 1977 to 2001.

Water Quality Evaluation

2000-01 Monitoring Results

Figure 21 shows all the pH, dissolved oxygen, and temperature data collected as instantaneous measurements during the study period for Crab Creek. Most temperature measurements made from June through August exceeded the 21º C Class B temperature standard.

There also were high pH excursions observed from May through July at many Crab Creek sites. Most pH measurements were taken in the early afternoon when high pH is associated with diurnal pH fluctuations found in Crab Creek (higher pH occurs in the afternoon due to photosynthetic utilization of carbon dioxide). This was despite the fact that Crab Creek is well buffered (alkalinity was >200 mg/L throughout the study period), which has the effect of dampening pH fluctuations.

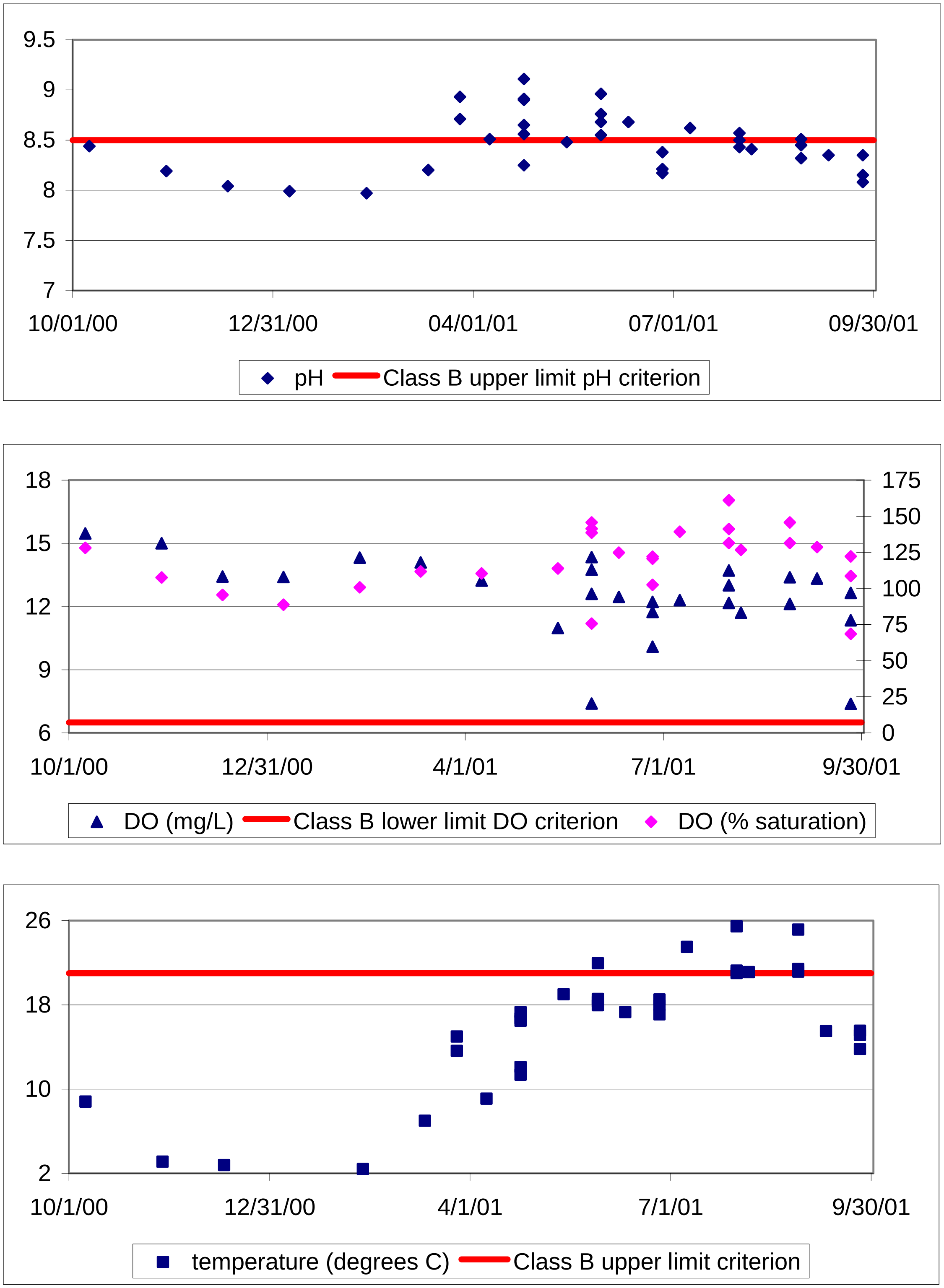


Figure 21. Data plots of all pH, dissolved oxygen, and temperature instantaneous data collected from all Crab Creek stations (CC1, CC2, CC3, CC4, CC5, and CC6) during the study period.

Likewise, dissolved oxygen also exhibits diurnal fluctuations in Crab Creek, with lower dissolved oxygen concentrations occurring at night and in early morning due to plant and algal respiration, and higher dissolved oxygen readings in the afternoon due to photosynthetic production of oxygen. Afternoon sampling on Crab Creek resulted in predominantly higher dissolved oxygen measurements and supersaturated conditions particularly through the summer. The only low dissolved oxygen measurements at station CC1 was taken on 9/25/01 at 8:10 A.M.

Phosphorus Loading to Moses Lake

Historically, during certain years Crab Creek has delivered large TP loads to Moses Lake during large winter/spring runoff events >500 cfs. These events discharge water down the entire length of Crab Creek, using portions of the creek channel that are usually dry year-round. The runoff is usually produced by large rain or snow events. The ground is usually still frozen, impeding infiltration and causing a large runoff of precipitation and snowmelt into the Crab Creek channel where erosive action transports stored sediment downstream. As much as 83% of the phosphorus load from Crab Creek to Moses Lake can occur in March and April during these events.

Horner et al. (1985) examined Crab Creek during a median flow year (winter-1982-83) and found limited contributions from the upper Crab Creek watershed above Brook Lake to Moses Lake. Although Lincoln County Conservation District has conducted limited nutrient sampling of the upper watershed, a more detailed source study of TP in the upper watershed would be beneficial during a high-flow event (greater than 500 cfs).

Much of upper Crab Creek has inadequate riparian cover. Because the channel is often dry, it has been left unprotected and has even been used for agriculture (e.g., plowing lines and cable irrigation lines go right across the channel in some places).

A large runoff event did not occur in Crab Creek during the 2000-01 study period, so water quality of such an event could not be characterized. However, the winter of 1996-97 produced a large runoff, and on March 27, 1997, Bain (1998) measured a TP concentration of 200 ug/L in Crab Creek (station CC1). Turbidity and total suspended solids of the turbid water were 40 NTU and 40 mg/L, respectively. Also, for that day the USGS reported an average daily discharge of 832 cfs, meaning the daily TP load to Moses Lake was 407 kg for that day alone. Assuming the 200 ug/L TP concentration were sustained through the month, and based on the USGS daily flow record for the month of March, Crab Creek would have discharged nearly 9000 kg of TP into Moses Lake that month.

Most of the variation in annual nutrient loading from Crab Creek to Moses Lake is a function of winter/spring runoff flow magnitude. These large runoff events do not occur after April. In effect, these events dictate the initial spring conditions of Moses Lake (March/April), although the settling of sediments to the lake bottom will eventually influence sediment oxygen demand and the release of bound phosphorus from the sediments later in the growing season. The summer flow from Crab Creek to Moses Lake is more predictable.

Daily TP and ortho-P loads from Crab Creek were developed for 2001 from seasonal and flow-weighted regressions using continuous flow data and monthly or bi-weekly sampling data at station CC1. The TP load regression had a RMSE of 0.8 kg/day with a coefficient of variation of 24.6% (n= 20). The ortho-P load regression had a RMSE of 0.2 kg/day with a coefficient of variation of 15.3% (n= 20).

The mean annual TP concentration and load in Crab Creek (data collected 1960 to 1989 at station CC1) was 97 ug/L and 3613 kg/yr, respectively. The mean annual TP concentration and annual TP load for the 2000-01 study period was 69 ug/L and 1343 kg/yr, respectively. Again, this study period was one of the lowest flow years since 1977, and the historical annual mean concentration and load were highly influenced by the variable winter/spring runoff events. This can be seen in a comparison of historical and study period mean monthly TP concentrations (Figure 22) and TP loads (Figure 23). Particularly, the study period had lower than average TP concentrations and loads in the months of February, March, and April. During the study period, Crab Creek concentrations of TP from May through September were 66% of average.

The mean annual ortho-P concentration in Crab Creek (station CC1) for the 2000-01 study period was 26 ug/L. Welch et al. (1989) reported annual mean soluble reactive phosphorus levels of 18 ug/L and 7 ug/L for the aggregate years of 1977-79 and 1986-88, respectively, at this station, which was greatly reduced from a mean of 32 ug/L in 1969-70. The study period mean ortho-P concentration from May through September was 13 ug/L (Figure 22). The total annual load of ortho-P to Moses Lake was 478 kg for the study period.

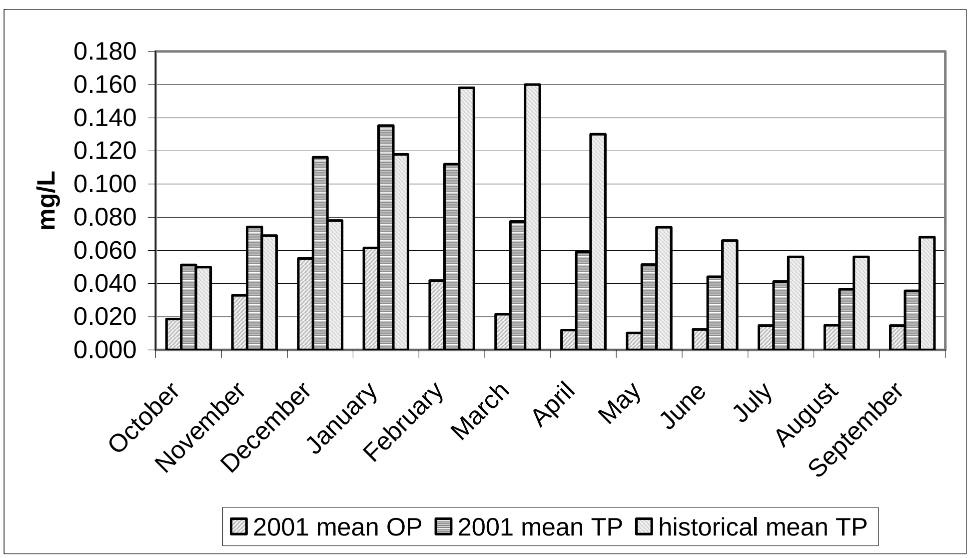


Figure 22. Ortho-P and TP concentrations in Crab Creek (station CC1) for the 2000-01 study period compared to historical TP concentrations.

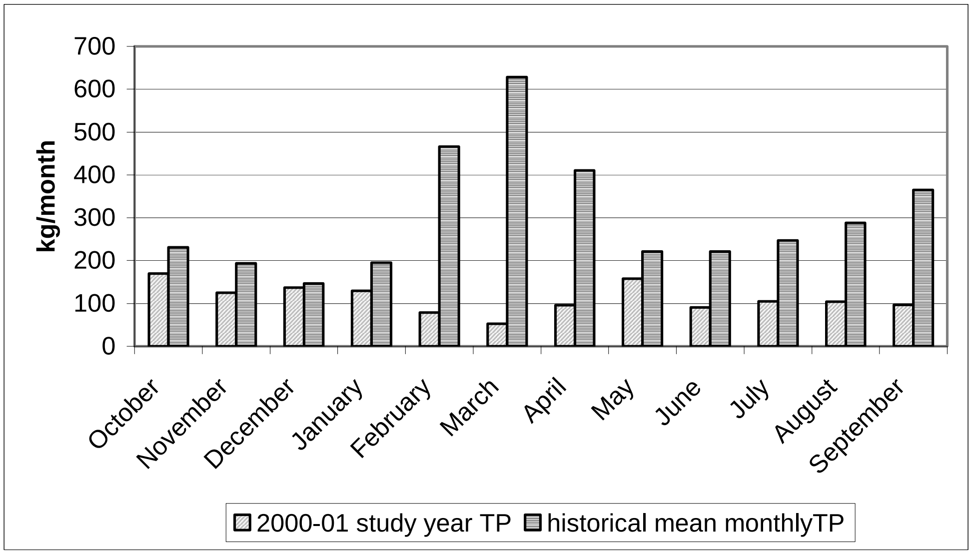


Figure 23. TP mean loads (kg/month) in Crab Creek (station CC1) for the 2000-01 study period compared to historical TP mean loads.

3. Rocky Coulee Wasteway

Historical Data Review

Rocky Coulee Wasteway is an artificial tributary to Moses Lake (via Crab Creek) constructed for the Columbia Basin Irrigation Project (CBIP) as a drain for irrigation return water and as a route for irrigation feed water. The wasteway also was constructed to drain natural runoff (baseflow). It contains the flow from the spring originating at the Columbia Basin Hatchery. The flow during the 2000-01 water year was dominated by feed water (i.e., Columbia River water). Carroll et al. (2000) presented historical flow data concerning feed water and the relation of their magnitude to climactic variation (e.g., there is an inverse relationship of feed water flow to natural flow from the Crab Creek watershed).

Hydrology

Figure 24 shows a Weibull distribution probability plot of the annual mean flows for Rocky Coulee Wasteway from 1977 through 2001. The 2000-01 study period had the fifth highest feed water within that time period, corresponding close to a 90^{th} percentile flow.

Water Quality Evaluation

2000-01 Monitoring Results

Rocky Coulee Wasteway is a specially classified surface water of the State of Washington as a tributary to Crab Creek, and is designated as Class B surface water. All instantaneous measurements of dissolved oxygen, pH, and temperature from the study period are presented in Figure 25. The measurements are compared with Class B standards. With the exception of some pH violations in the mid-summer months, Rocky Coulee Wasteway had acceptable pH, dissolved oxygen, and water temperature during the 2000-01 study period, often meeting the water quality criteria of a Class A stream. Of course, the water quality of Rocky Coulee Wasteway was greatly influenced by the feed water of high-quality Columbia River water.

Columbia Basin Hatchery Spring

The Columbia Basin Hatchery was evaluated from April through September 2001 for baseflow and nutrient loading. The spring at the hatchery flows year-round, with generally higher flows in the summer associated with irrigation recharge to groundwater. A majority of the spring water is diverted through the hatchery complex as normal process water. Solids are removed periodically to a settling pond. The settling pond discharges downstream into the spring channel just downstream of where all of the normal process water is returned. The spring channel flows south for about one and half miles until it discharges to Rocky Coulee Wasteway.

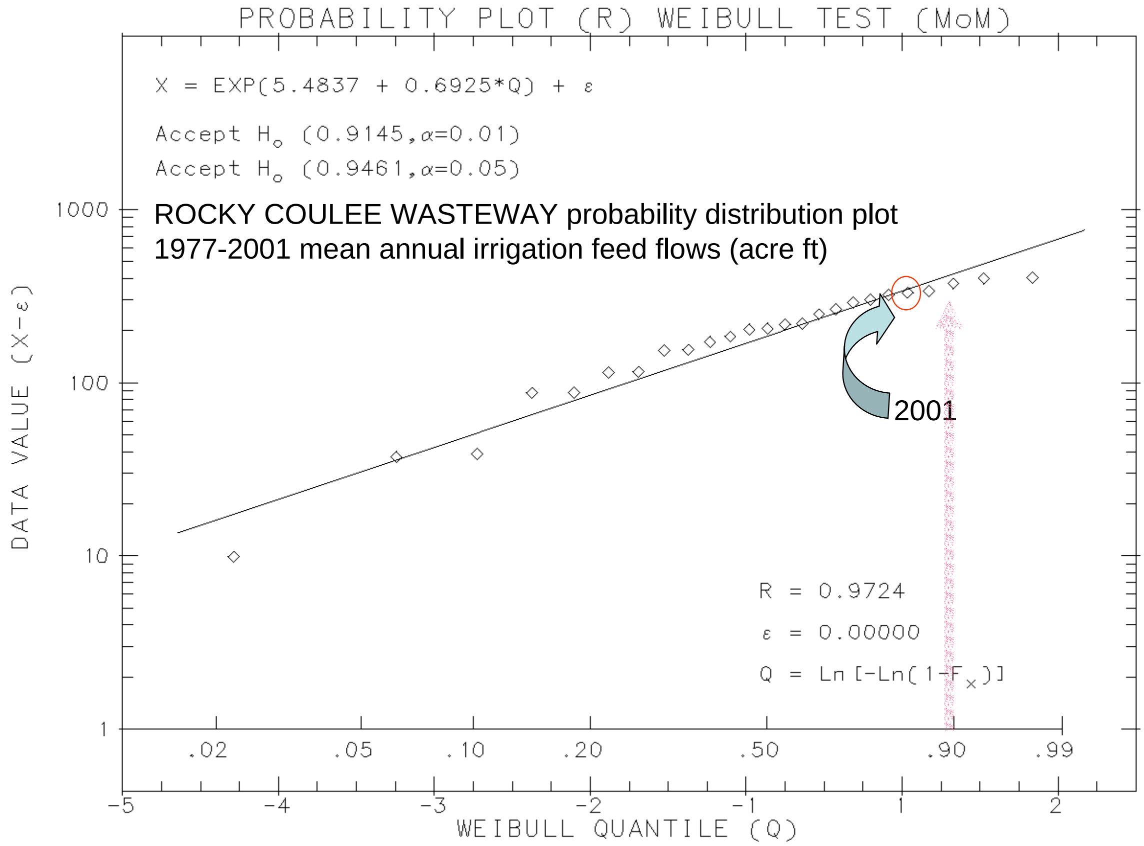
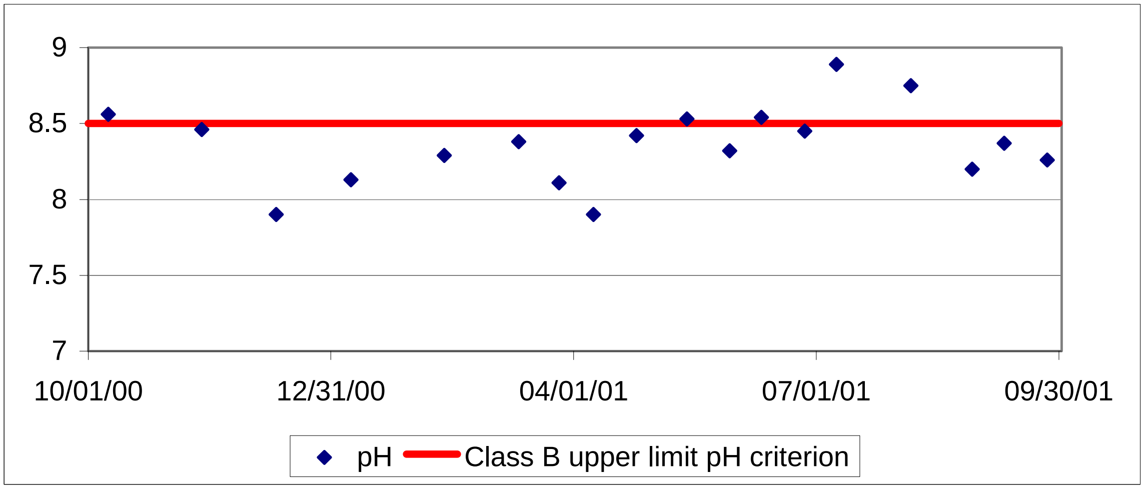
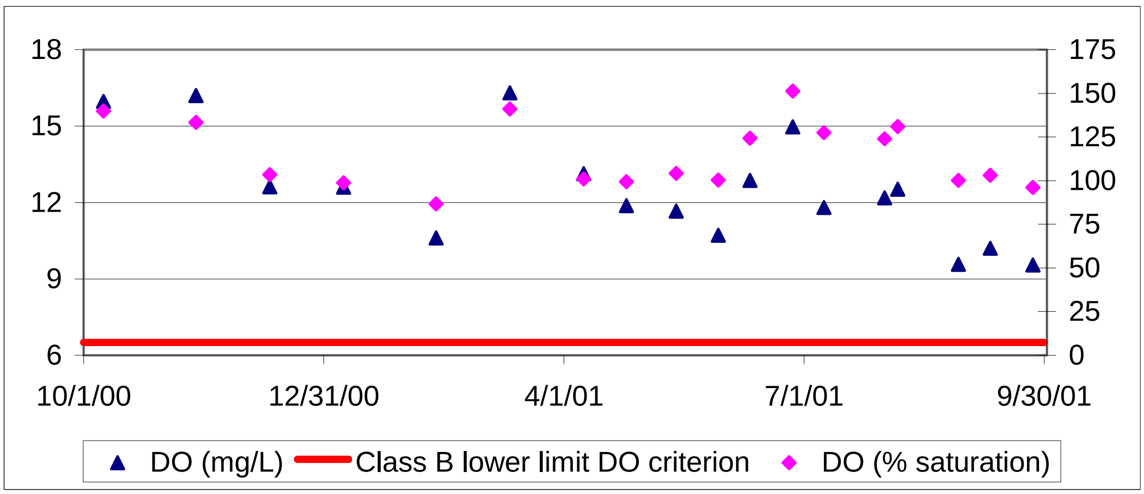


Figure 24. Distribution probability plot of mean annual feed water discharges to the Rocky Coulee Wasteway from 1977 to 2001.

The spring supplies most of the baseflow found in Rocky Coulee Wasteway. During 2001, the flow from the spring steadily increased from 15 cfs in May to just over 22 cfs in September. From 1977 to 1979, Patmont (1980) estimated the annual baseflow in Rocky Coulee Wasteway to be 35 cfs. The flow in 2001 was probably lower because of less sub-surface recharge.

Spring concentrations of TP and ortho-P had an average increase of 16% and 13%, respectively, downstream of all Columbia Basin Hatchery effluent discharges for the 2001 period (Figure 26). The average TP concentration was 87 ug/L for the period, with 67% of that in dissolved phase (ortho-P). The monthly average TP loads for the Columbia Basin Hatchery, the spring, and the total combined are presented in Figure 27.





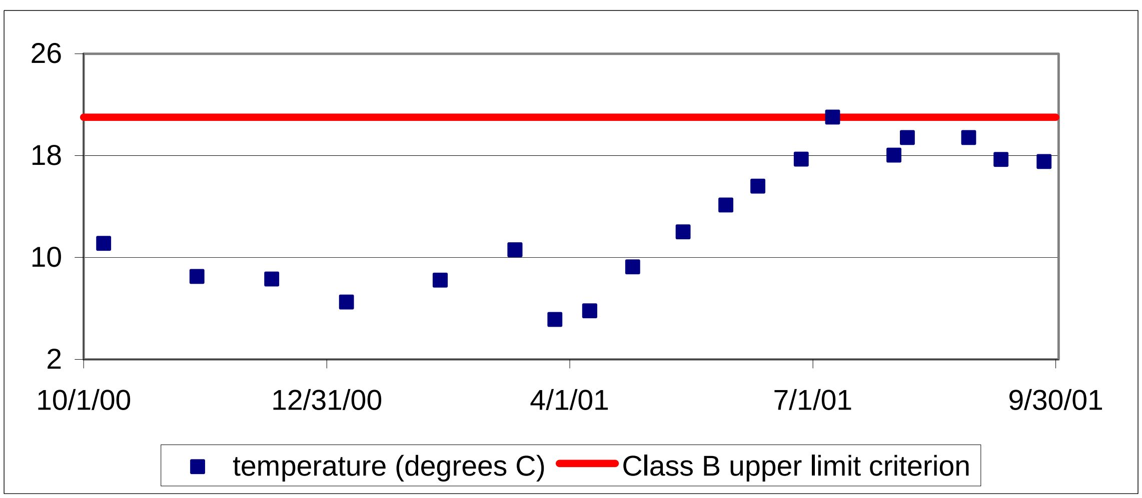


Figure 25. Data plots of all pH, dissolved oxygen, and temperature instantaneous data collected from Rocky Coulee Wasteway at Rd. K (station RC1) during the study period.

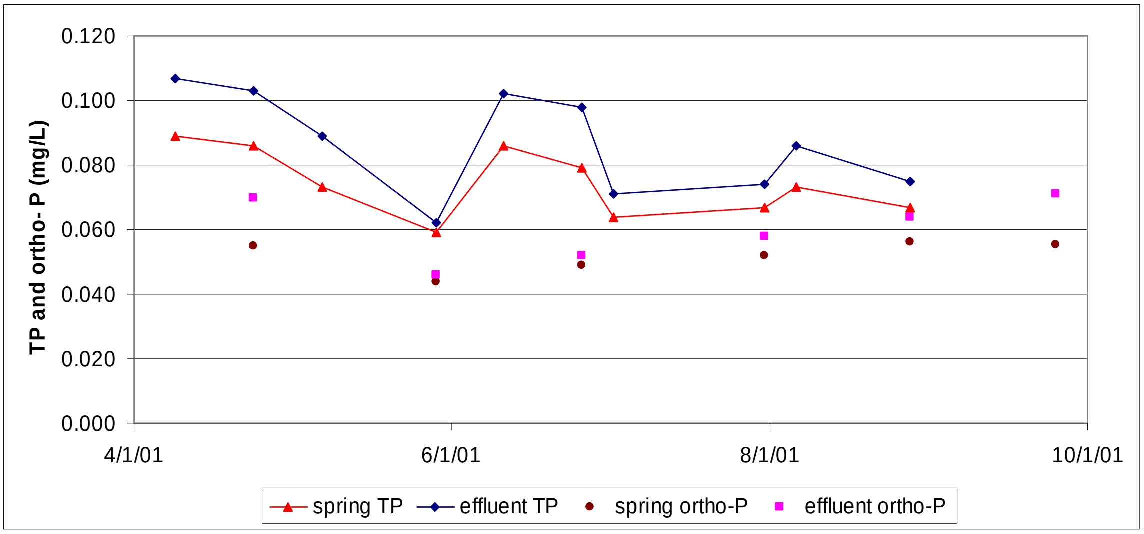


Figure 26. Comparison of spring and downstream (of effluent discharge) concentrations of TP and ortho-P at the Columbia Basin Hatchery.

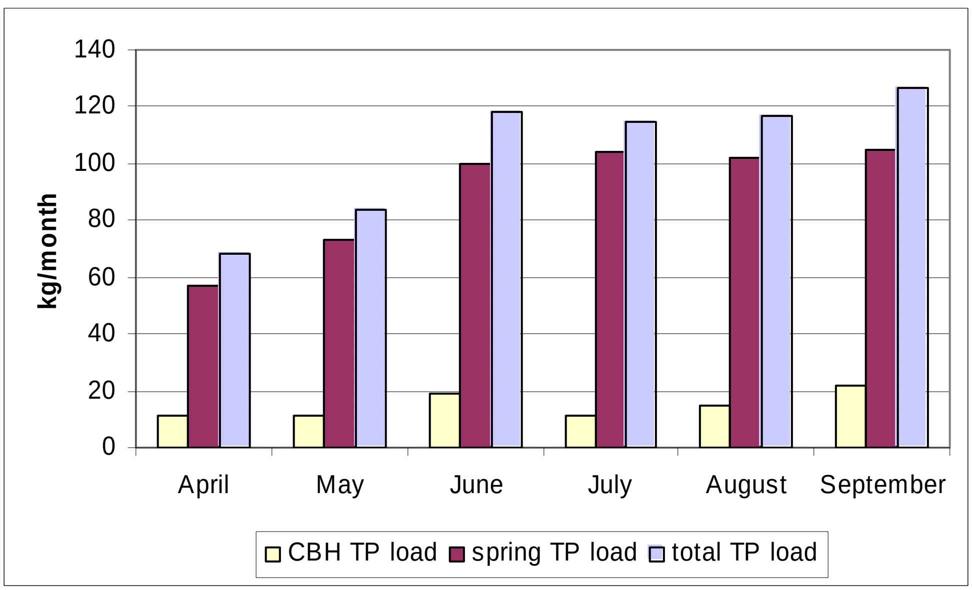


Figure 27. Comparison of apportioned TP loads from the Columbia Basin Hatchery and spring with the total TP load to Rocky Coulee Wasteway.

Phosphorus Loading to Moses Lake

Daily TP and ortho-P loads from Rocky Coulee Wasteway were developed from seasonal and flow-weighted regressions using continuous flow data and monthly to bi-weekly sampling data at station RC1. The TP load regression had a root mean squared error (RMSE) of 3.2 kg/day with a coefficient of variation of 20% (n= 20). The ortho-P load regression had a RMSE of 1.3kg/day with a coefficient of variation of 34% (n= 20).

The TP concentration of the water that Rocky Coulee Wasteway discharged to Crab Creek depended on the ratio mix of Columbia River water to baseflow water (Columbia Basin Hatchery spring) as can be seen in Figure 28. When discharges were high from feed water (i.e., very high ratio of Columbia River Water to baseflow), the TP concentrations were generally low, dominated by low-nutrient Columbia River water.

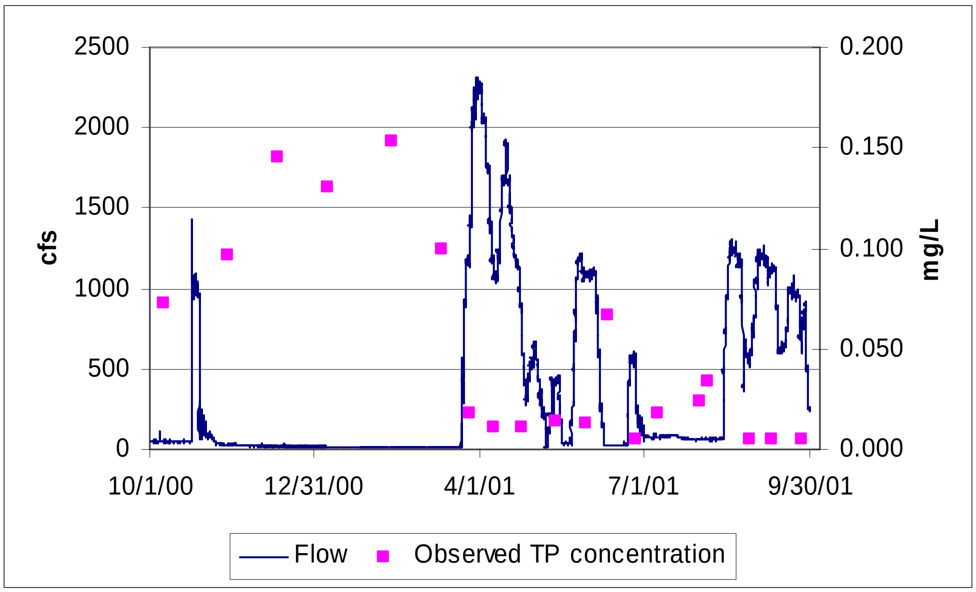


Figure 28. Comparison of observed TP concentrations in Rocky Coulee Wasteway (station RC1) with the continuous flow record of Rocky Coulee Wasteway.

A sampling site was selected upstream of any baseflow discharges into Rocky Coulee Wasteway (station RC2) to characterize the Columbia River water entering from the East Low Canal. At this station the March through September TP and the ortho-P concentrations were at or below their respective detection limits of 10 ug/L and 5 ug/L, with two exceptions for TP (15 ug/L in March and 13 ug/L in May). The Columbia River water provides a low-phosphorus concentration water supply to Moses Lake.

While the concentration of TP in the feed water was low, the quantity of water was substantial enough in some months to result in large loads of TP to Moses Lake, particularly in March, April, and May (Figure 29). This still resulted in a dilution because the higher TP concentration lake-water was displaced and washed out of the outlet. The calculated annual TP load from Rocky Coulee Wasteway to Moses Lake for the study period was 4,570 kg. From May to September, the contribution was 1,580 kg with 35% of that attributable to the Columbia Basin Hatchery and its spring (Figure 29). The proportion of ortho-P in the TP load of the feed water was relatively low (Figure 30).

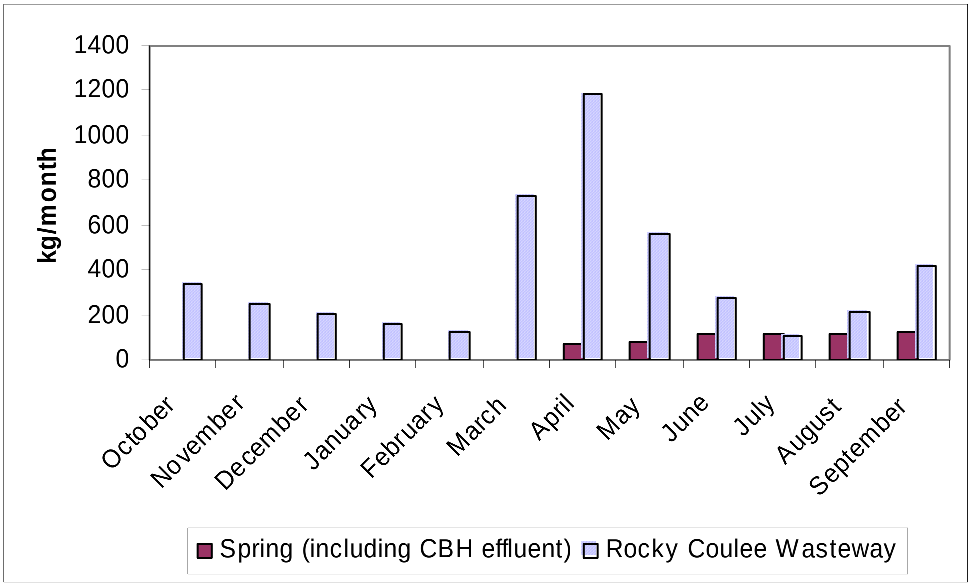


Figure 29. Comparison of the TP load attributable to the Columbia Basin Hatchery spring with TP loads from Rocky Coulee Wasteway during the 2000-01 study period. (October through March data not available for the spring.)

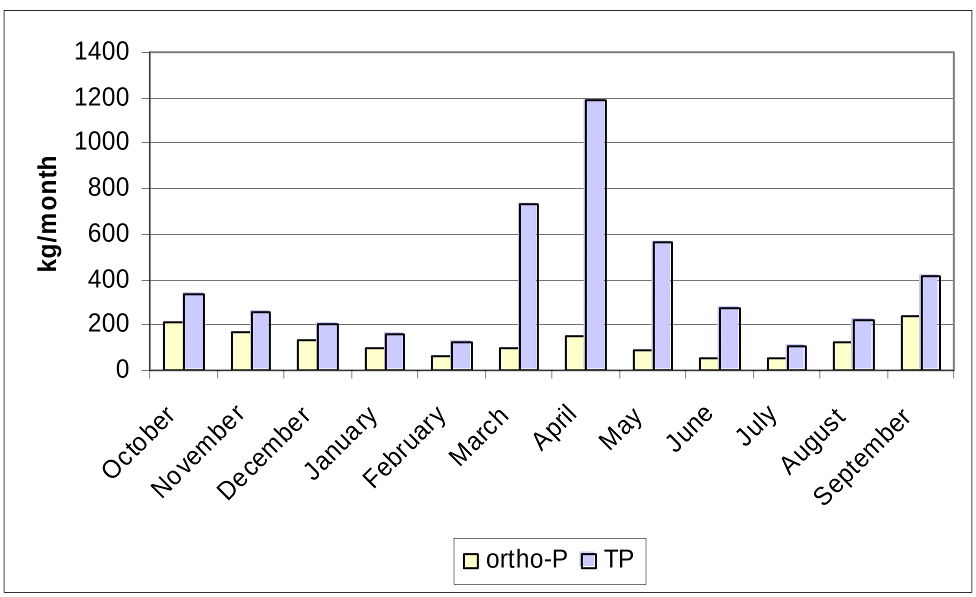


Figure 30. Comparison of ortho-P and TP loads in Rocky Coulee Wasteway for the 2000-01 study period.

4. Moses Lake

Historical Data Review

Moses Lake has been studied since the early 1960s. Carroll et al. (2000) provided a summary of some of the major studies and their conclusions. Readers are advised to reference the original studies reviewed by Carroll et al. (2000) for analytical details.

Hydrology

The hydrology of Moses Lake is complex even without anthropogenic (human-caused) influences. Moses Lake water level was unregulated until 1929 when the first dam was built on the outlet. Prior to 1929, the vagaries of climatic events most likely kept Moses Lake in a constant state of change. Drought conditions, flood events from Crab Creek, fluctuating groundwater discharges (to Rocky Ford Creek, Crab Creek, and the lake itself), and changing water levels (i.e., compromised or shifting sand dunes changing the elevation at the outlet) all would have affected the lake hydrology, as well as the water quality, prior to human-caused changes in the Columbia Basin.

Extensive lake regulation began with the arrival of the Columbia Basin Irrigation Project (CBIP) in the 1950s, including the addition of another dam in 1968, resulting in some predictable stability (i.e., regulated lake stage). Still, this stability is only achieved by compensating for or dampening the effects of the natural climatic cycles. For example, during the 2000-01 study period, Rocky Ford Creek and Crab Creek had below average discharges to Moses Lake and yet were supplemented by the fifth highest feed water addition through Rocky Coulee Wasteway. Enough Columbia River water was diverted through Moses Lake to completely fill the lake twice in 2001 (Figure 31).

As explained in Carroll et al. (2000), most of the feed water delivered to Moses Lake is routed downstream to Potholes Reservoir where it is used for irrigation in the southern part of the CBIP. Moses Lake is not a storage reservoir for the CBIP, like Potholes Reservoir, but is rather a part of the conveyance path for feed water. The U.S. Bureau of Reclamation (USBR) does not deliver water through Moses Lake unless there is a downstream irrigation need, though an agreement was made in 1977 to use Moses Lake as one of the more consistent feed routes. The USBR does have an agreement to maintain a summer lake stage in Moses Lake. Moses Lake and Potholes Reservoir are filled up in the early spring (from winter stage to summer stage) either by natural runoff or feed water, but usually a combination of the two. However, a large winter/spring runoff from Crab Creek can fill Moses Lake, as well as Potholes Reservoir, alleviating the need to have any feed water, as in 1984 when no feed water was diverted through the lake. The USBR does not consider the quality of the water used to maintain lake stage in Moses Lake and has not conveyed feed water (i.e., high quality Columbia River water) through Moses Lake for the sole purpose of enhancing water quality.

In summary, the hydrology of Moses Lake has been substantially altered by the CBIP, probably increasing its beneficial uses by maintaining a regulated lake stage and improving water quality with feed water additions.

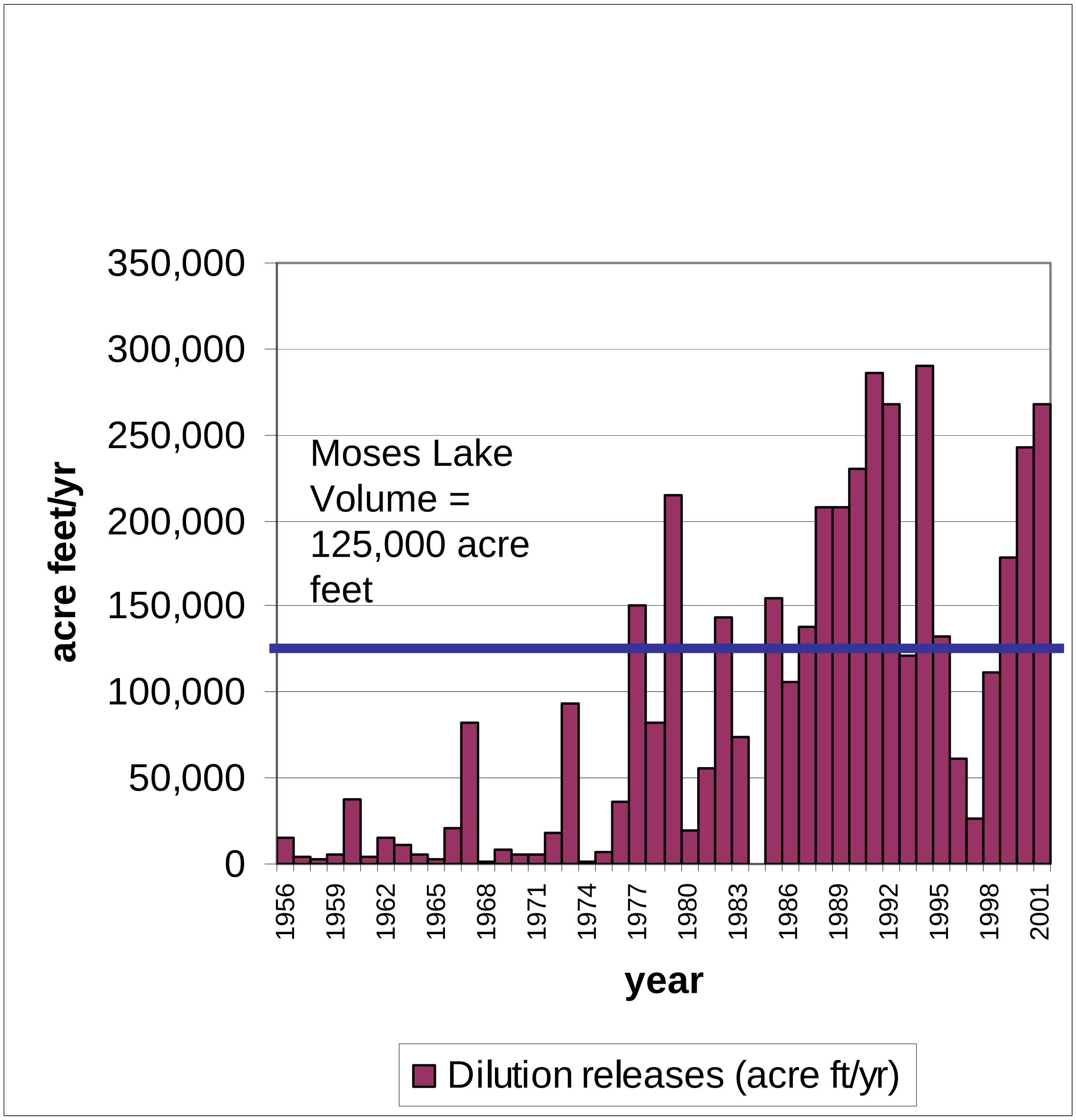


Figure 31. Annual feed water of Columbia River water through Moses Lake from 1956 to 2001, compared with the volume of Moses Lake.

2000-01 Water Budget

The water budget for the 2000-01 study period was developed for the water balance calibration for the CE-QUAL-W2 model (see below). All efforts were made to accurately measure all surface inflows and outflows. The rating curve for Rocky Ford Creek had a RMSE of 0.9 cfs (CV = 1.3%; n=5) for the whole range of flows. The rating curve for Rocky Coulee Wasteway had a RMSE of 34.9 cfs (CV = 5.5%; n=8) for the whole range of flows. Crab Creek was gaged and rated by the USGS.

The two outlets, both to Potholes Reservoir, have been historically difficult to measure. Not only has the extremely high velocity of the water passing through the gates been difficult to measure with velocity meters, but day-to-day and seasonal operational changes at the outlets create very different hydraulic regimes. The north outlet, operated by the Moses Lake Irrigation and Rehabilitation District, only had one gate open and in one position for the 2000-01 study period. The flow there was calculated as a function of head difference in Moses Lake and Potholes Reservoir (Appendix C).

The south outlet is the main outlet and is operated by the USBR. This structure has five radial arm gates and had never been rated. Flow measurements were made by Ecology and USBR in front of the south outlet structure using acoustic Doppler current profilers during various flow conditions (e.g., full pool, low pool, submerged backwater, unsubmerged backwater, restricted flow, and unrestricted flow). Continuous flow was then calibrated and modeled by Northwest Hydraulic Consultants using HEC-RAS version 3.0. The simulated flows had a RMSE of 71.7 cfs (CV = 7.8%; n=13) for the whole range of flows and operational regimes.

A water budget was calculated by subtracting inflows from outflows, while adjusting for a change in storage on a continuous basis (every hour) throughout the 2000-01 study period. In addition the water budget was fine-tuned using a water balance utility for CE-QUAL-W2 that matches simulated and actual water levels in the lake (see below). The resulting residual was averaged daily and applied as a net groundwater inflow if positive or as a net groundwater outflow if negative. The distribution of groundwater around the lake followed an analysis reported by Pitz (2003). Pitz also made estimates of groundwater flux ranges for different areas of Moses Lake. The 2001 residual applied as groundwater fell within the ranges reported by Pitz (Figure 32). Comparison of simulated chloride using the CE-QUAL-W2 model with field data (see below) confirmed this approximation of groundwater inflow to Moses Lake. CE-QUAL-W2 has an internal evaporation model that was used to estimate evaporative water loss.

Figure 33 presents the summary of inflow contributions for the hydrologic water year from October 2000 through September 2001. The inflows were dominated by feed water delivered through Rocky Coulee Wasteway. Direct groundwater inflows, Rocky Ford Creek, and Crab Creek each contributed 18%, 11%, and 5%, respectively.

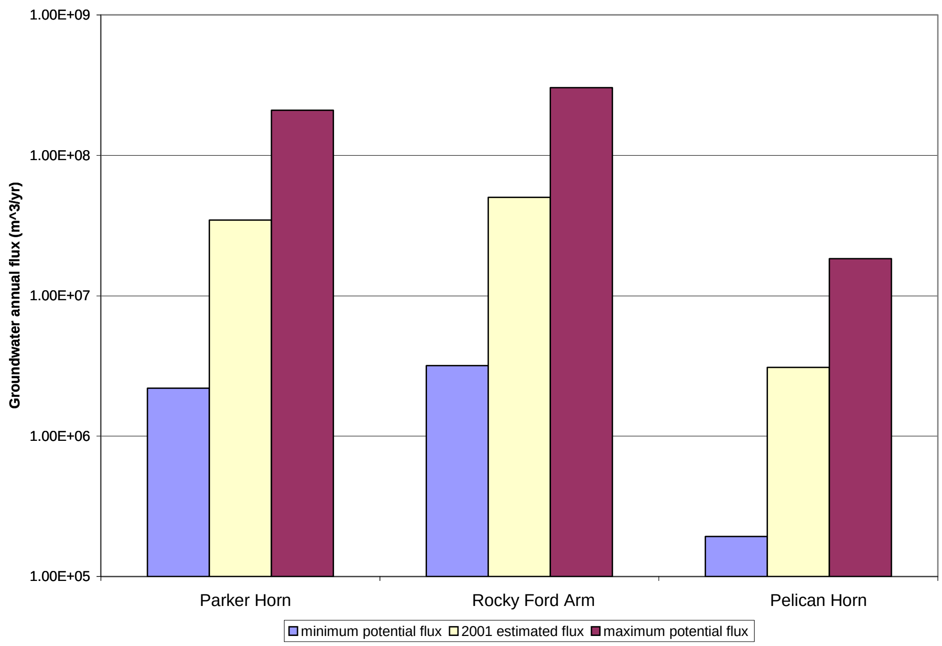


Figure 32. Comparison of 2001 groundwater flux with minimum and maximum potential fluxes reported by Pitz (2003).

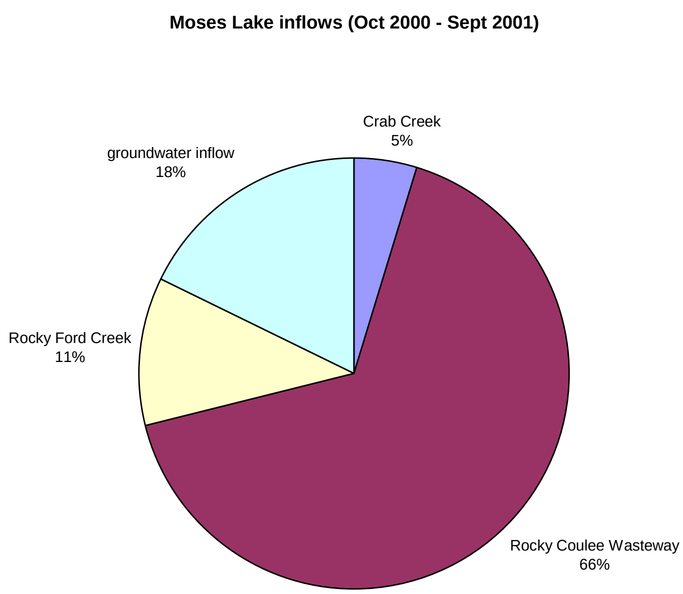


Figure 33. Summary of percent contribution from various inflows to total inflow to Moses Lake from October 2000 through September 2001 (the study period).

Water Quality Evaluation

2000-01 Monitoring Results

By historical comparison, Moses Lake had greatly improved water quality during the 2000-01 study period. There were no significant blue-green algae blooms, and the average in-lake TP concentration for the whole lake was 38 ug/L from May through September. Obviously, the amount of feed water added to Moses Lake was substantial during 2001 and favorably impacted the water quality. The average monthly fraction of feed water in Parker Horn ranged from 29% in July to 65% in September. From May through September, the whole lake average fraction of feed water was 27%. Still, Moses Lake would have been considered a moderately productive eutrophic system in 2001.

Temperature, dissolved oxygen, and pH

Time and depth plots of temperature and dissolved oxygen (DO) for the two deep basins (Cascade and South basins; stations ML-2 and ML-3) are presented in Figures 34 and 35. A time and depth plot of pH for the Cascade basin is presented in Figure 36. Moses Lake is relatively shallow and polymictic which means it can mix or circulate several times per year. Beginning in April, weak thermal stratification occurred in Moses Lake because of uneven heating of the water column from solar radiation resulting in the development of water density gradients or layers, typically referred to as the epilimnion (upper water) and the hypolimnion (deeper water). Strong wind events periodically mixed the water column and disrupted the stratification, as in May and July. The strongest period stratification occurred in August. The entire water column was mixed by the end of September, due to wind mixing and waning solar radiation.

During stratification periods, DO was depleted in the isolated hypolimnion due to oxidation of organic materials. The resulting anoxia affected the solubility of phosphate in the sediments, causing a release of phosphate, as well as an increase in conductivity and other soluble constituents, to the overlying water. Generally, DO and pH levels in the euphotic zone were elevated (maximum supersaturated DO greater than 15 mg/L and pH greater than 9.0) during periods of high algal productivity and lower during periods of low algal productivity. There were substantial periods when much of the water column was below 8 mg/L.

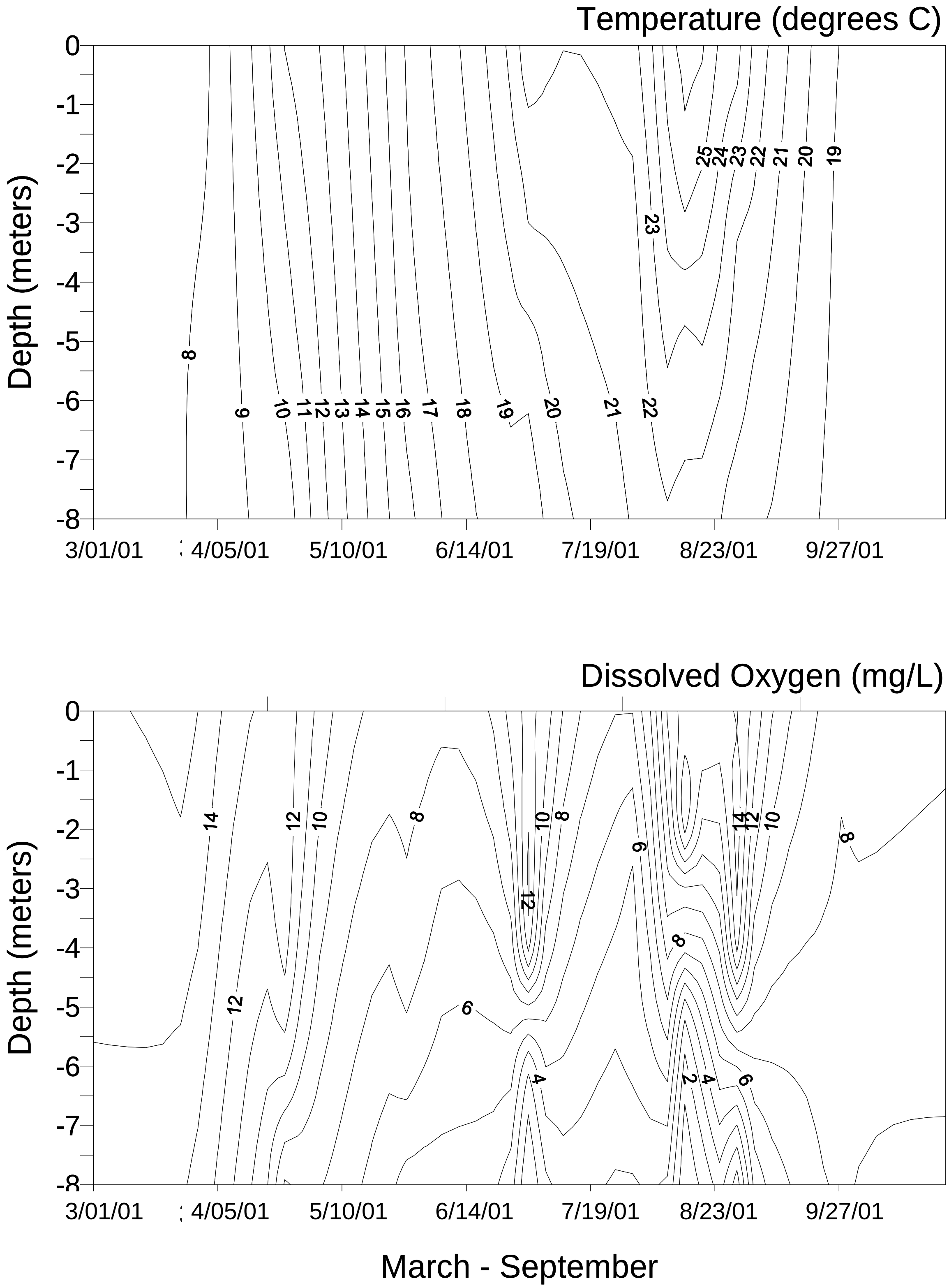


Figure 34. Temperature and dissolved oxygen isopleths based on field data collected in the Cascade basin of Moses Lake (station ML-2).

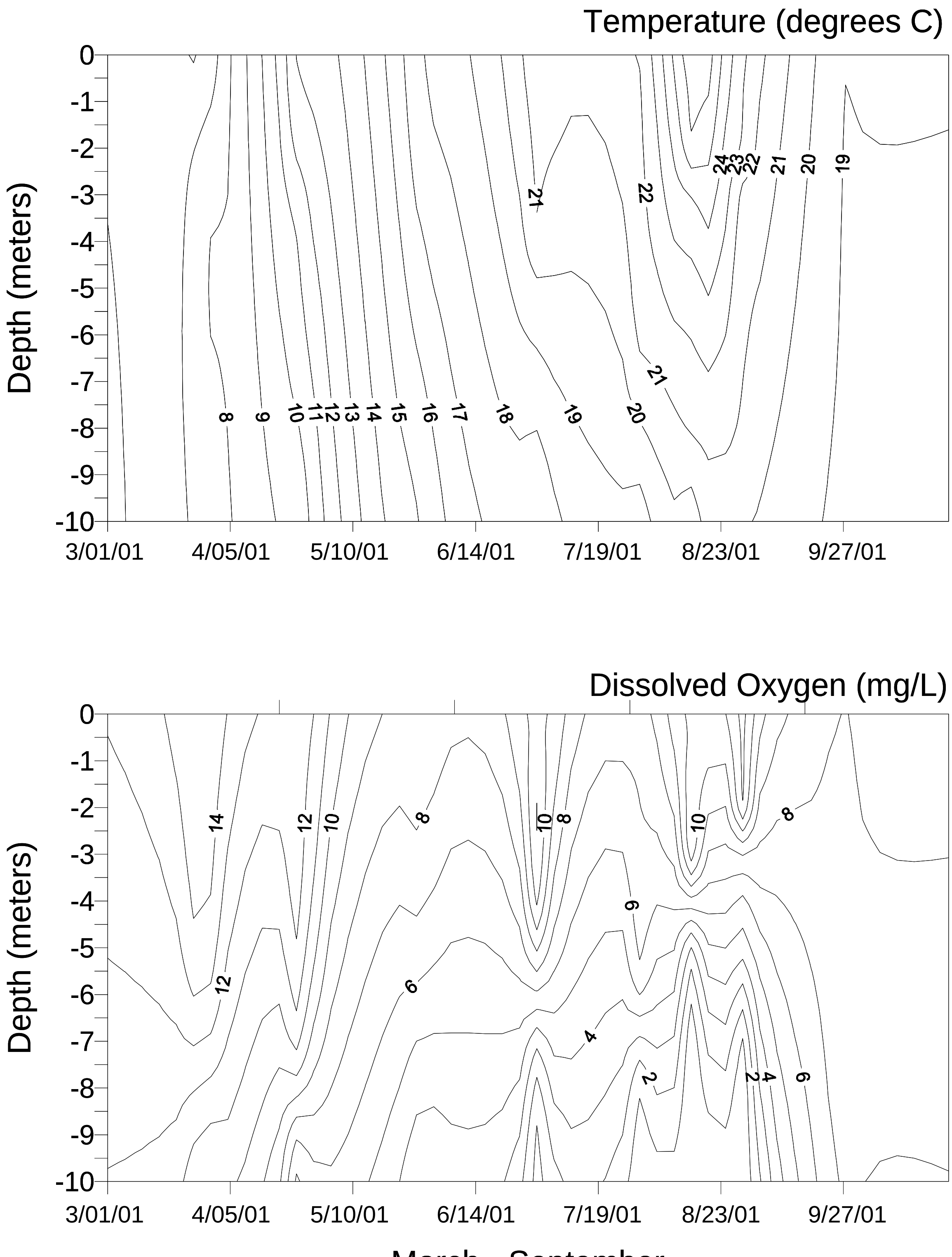


Figure 35. Temperature and dissolved oxygen isopleths based on field data collected in the South Basin of Moses Lake (station ML-3).

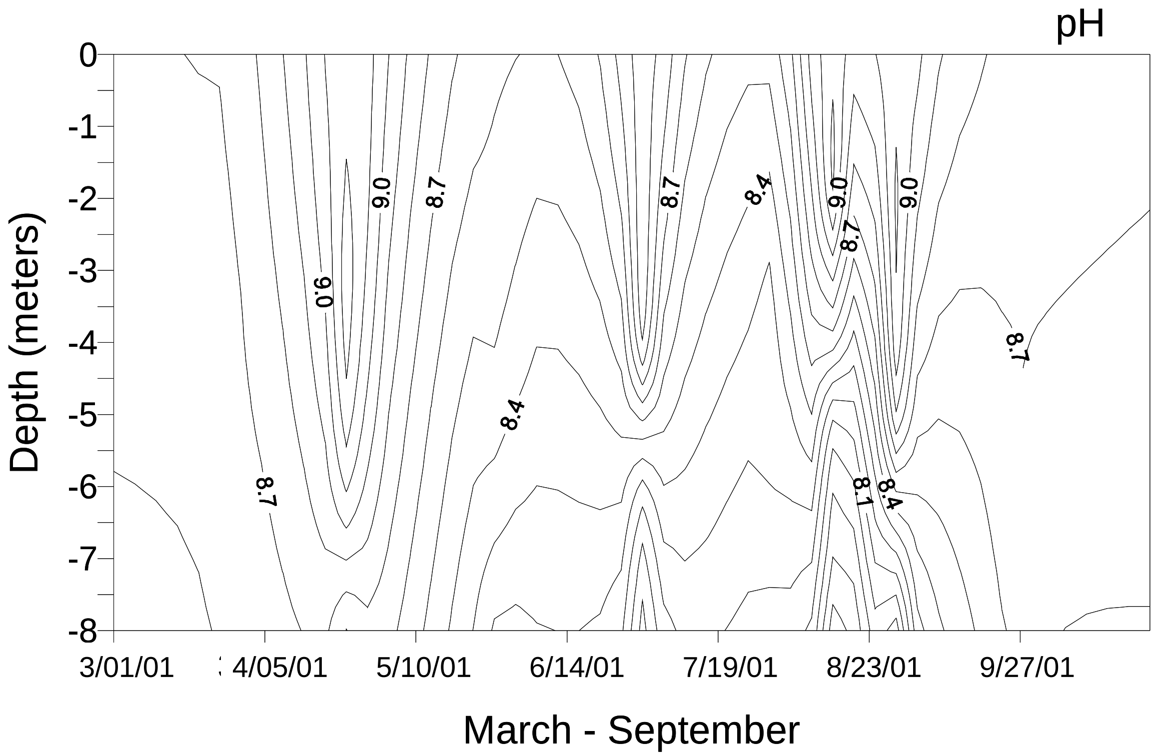


Figure 36. pH isopleths based on field data collected in the Cascade basin of Moses Lake (station ML-2).

Algae

Algal species densities and biomass were assessed March through September in Moses Lake. Densities and biovolumes of the major algal groups are presented as stacked plots in Figure 37. The first sampling in late March took place during a spring diatom bloom almost completely dominated by *Asterionella formosa*. This species is very common as an early dominator of spring algal blooms in mesotrophic and eutrophic lakes, when phosphorus is limiting and there is plentiful silica (Reynolds, 1984). By late April, the diatom bloom had experienced a successional change in species and was newly dominated by *Fragilaria pinnata* with sub-dominants, *Fr. crotenensis* and *Melosira ambigua*.

After the spring diatom bloom crashed in May, there was a transitional lull in algal productivity until late June when summer biomass began to build. The summer biomass predominantly consisted of diatoms and dinoflagellates, particularly *Melosira granulata*, *Fragilaria crotonensis*, *Rhodomonas minuta*, and *Cryptomonas erosa,* though a number of other algal groups including a few blue-greens were in the assemblage.

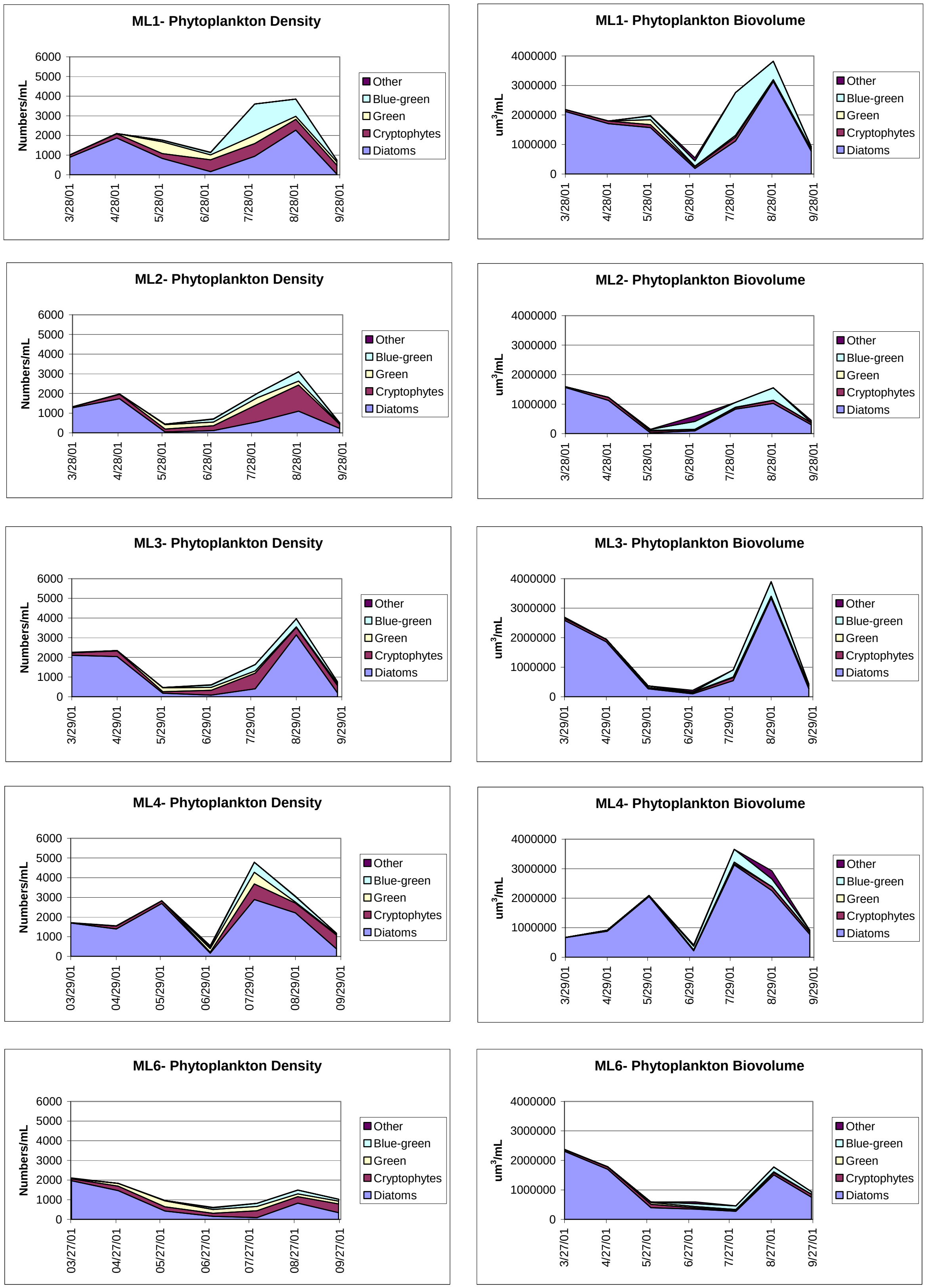


Figure 37. Densities and biovolumes of major algal groups in Moses Lake at all stations. Graphs are stacked line plots where algal groups are cumulatively stacked for each sampling date.

There was an exception in the upper part of Rocky Ford Arm (ML-1) with its rich nutrient replenishment from Rocky Ford Creek and relative isolation from the added feed water. This upper part of Moses Lake continued to experience high algal biomass through May with the biomass dominated by the diatom, *Fragilaria crotenensis,* and the green algae, *Oocystis pusilla*. This succession led to a blue-green algal bloom in July and August composed of *Aphanizomenon flos-aquae*; however, a substantial diatom biomass composed of *Melosira granulata* developed in August as well.

For the most part, though, during the 2000-01 study period, Moses Lake had the seasonal algal succession typical of a less productive, eutrophic lake system. The spring diatom bloom has always been common to Moses Lake, but the summer algal biomass in Moses Lake varies in relation to the nutrient supply. Historically, as a highly eutrophic lake system, Moses Lake has been dominated in the summer by nitrogen-fixing blue-green algae blooms consisting of *Aphanizomenon* and *Microcystis* species, even since dilution began in 1977 (Welch et al., 1989). The development of a summer diatom succession in 2001 was perhaps due to the timing and exceptional quantity of low-nutrient feed water added to Moses Lake. While silica concentrations can be limiting for summer diatom development, dissolved silica concentrations were still 5 to 10 times higher than limiting levels (<0.5 mg/L) in Moses Lake at the end of the 2001 growing season, discounting silica as a limiting resource.

Lake Water Quality Modeling

Purpose and Scope

A water quality model of Moses Lake was used to better understand the fate and transport of TP in the lake. Using the model as a diagnostic tool, the various physical, biological, and chemical processes that affect the fate and transport of TP were simulated. The model was used to assess the capacity of Moses Lake to assimilate TP with respect to maintaining the proposed in-lake TP criterion of 50 ug/L during a worst-case, little dilution year. The model then was used as a tool to evaluate various management alternatives in order to develop a phosphorus allocation plan based on meeting the in-lake TP criterion.

Model Description

CE-QUAL-W2 simulates the hydrodynamics, water temperature, and water quality of a water body in two dimensions. The model simulates longitudinal and depth dimensions while averaging along the lateral dimension (width of the water body). Therefore, CE-QUAL-W2 is best applied to water bodies with distinct variations in length and depth but with few distinctions in width. Moses Lake is an ideal application for CE-QUAL-W2 because of its dendritic morphology (long and narrow branches). CE-QUAL-W2 is a dynamic model, and the fundamental fate and transport of TP in Moses Lake is dependent on dynamic conditions.

Numerical algorithms within CE-QUAL-W2 dictate how the sources, sinks, and transport of water, heat, and constituents are simulated. A description of the model's conceptual framework and numerical expressions is available in the user manual by Cole and Wells (2002) and at the following website: www.ce.pdx.edu/w2/.

Model Setup

CE-QUAL-W2 was calibrated to water quality in Moses Lake for February 19 through September 30, 2001 (julian day 415 through 630 in the model). CE-QUAL-W2 is a complex water quality model and requires many types of boundary, calibration, and meteorological data. The data used to set up the Moses Lake application were collected by several organizations (Table 11).

Table 11. Sources of boundary, calibration, and meteorological data used in the Moses Lake CE-QUAL-W2 model.

Data Type	Data Source
Bathymetry	Sylvester (1964), Ecology
Discharge and withdrawal rates	USGS, USBR, Ecology, Moses Lake Irrigation and Rehabilitation District
Water elevations of Moses Lake and Potholes Reservoir	USGS, USBR
Water Temperatures	Ecology, USBR
Meteorology	National Climactic Data Center (Moses Lake airport), Hanford Meteorological Station
2000-01 water quality data	Ecology
Historical water quality data	Ecology, Patmont (1980), Welch et al. (1989), Bain (1998)

Moses Lake Bathymetry and Model Grid

The model grid of Moses Lake was developed from a bathymetric map published by Sylvester and Olglesby (1964). The bathymetric data were field-checked by Ecology in 2001. The bathymetry was found to be unchanged in most of the lake, except for Rocky Ford Arm and the Cascade basin (station ML-2). The Rocky Ford Arm was shallower than the old data by up to one foot. The Cascade basin lacked the deepest section of the basin present in the 1960s. In fact, in no place did the depth exceed 9.0 meters (>30 ft) in the Cascade basin. Sediment focusing may explain the increased accumulation of sediments in the Cascade basin. The South Basin (station ML-3) morphology had not changed since the 1960s. The narrow and shallow causeway under Highway 90 between the two main basins may act as a dike to the passage of settling solids originating from the tributaries or up-lake to the South Basin.

The corrected bathymetric map was scanned and brought into Arcview 3.2. With Image Analyst extension, the image was geo-referenced and rectified to existing ortho-photo coverage of the lake. The resulting image was made into a polygonal shape file and then sliced into 74 model segments (Figure 38), developing a table of segment area-to-depth measurements for use as a bathymetric input file for CE-QUAL-W2. There was a maximum of 12 depth layers for each segment. Each layer was approximately one meter in depth.

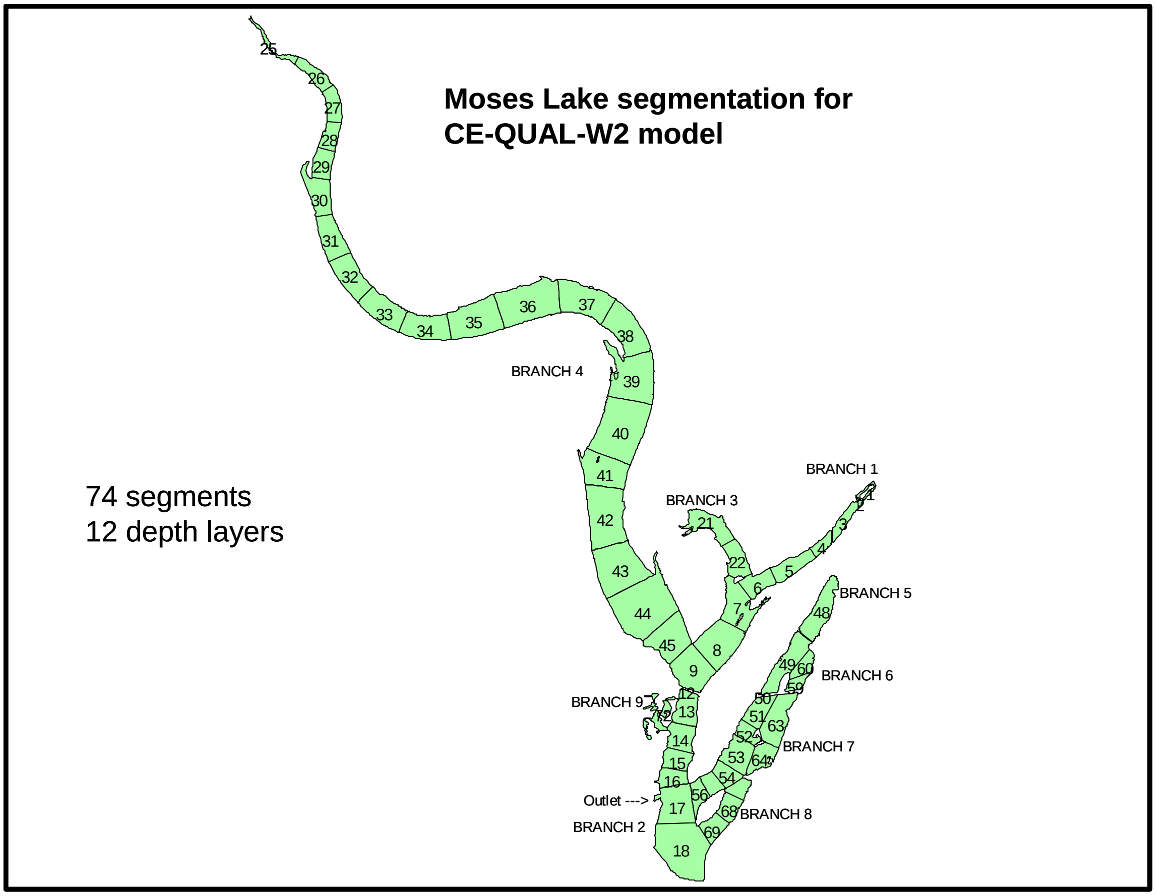


Figure 38. Model segments of Moses Lake showing segments and branches used in CE-QUAL-W2.

Volumetric calculation of the segments also was done following the methodology outlined by Wetzel (1983). Figure 39 shows a very favorable comparative plot of volume-to-elevation curve for Moses Lake developed by volumetric calculation and a volume-to-elevation curve developed from CE-QUAL-W2 bathymetric output. It is essential to accurately represent the geometry of Moses Lake to accurately model the hydrodynamic movement of water through the lake.

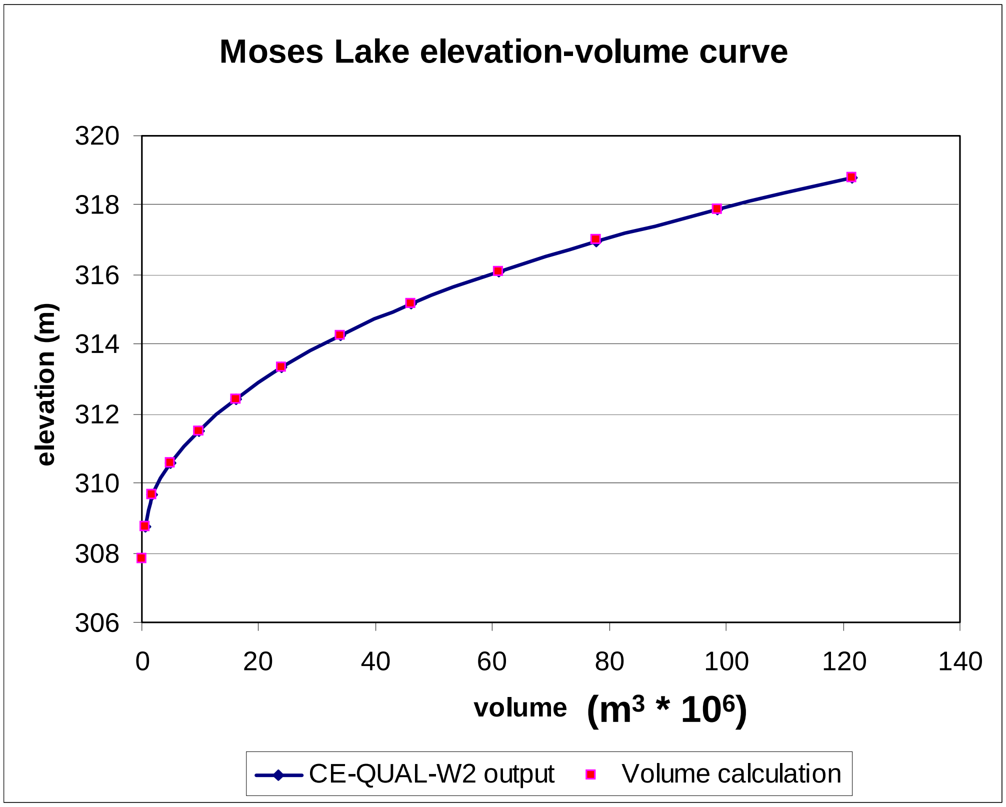


Figure 39. Moses Lake volume-to-elevation curves as represented by CE-QUAL-W2 and as an independent volume calculation.

Water Balance

All known major surface inflows and outflows to Moses Lake were measured for the 2000-01 study period. The initial water balance was based on the difference of continuous discharge measurements of the outflows (north and south outlets) and the inflows (Rocky Ford Creek, Crab Creek, and Rocky Coulee Wasteway), taking into account the change in storage of the lake (Moses Lake stage recorded by USGS). From this water budget, a residual was calculated that consisted of ungaged inflows and outflows (e.g., net groundwater inflow/outflow and irrigation withdrawal) as well as error in the measurements of gaged surface inputs and outputs (e.g., error in rating curves and error in volumetric displacement in the Moses Lake bathymetry). Additionally, CE-QUAL-W2 incorporates a water balance utility that fine tunes the residual by comparing the simulated Moses Lake stage with the USGS stage during each specified time-step of a model simulation and creating a correction file of hourly residual flows. Figure 40 shows a favorable comparison of the USGS water level data to model results for the 2000-01 study period.

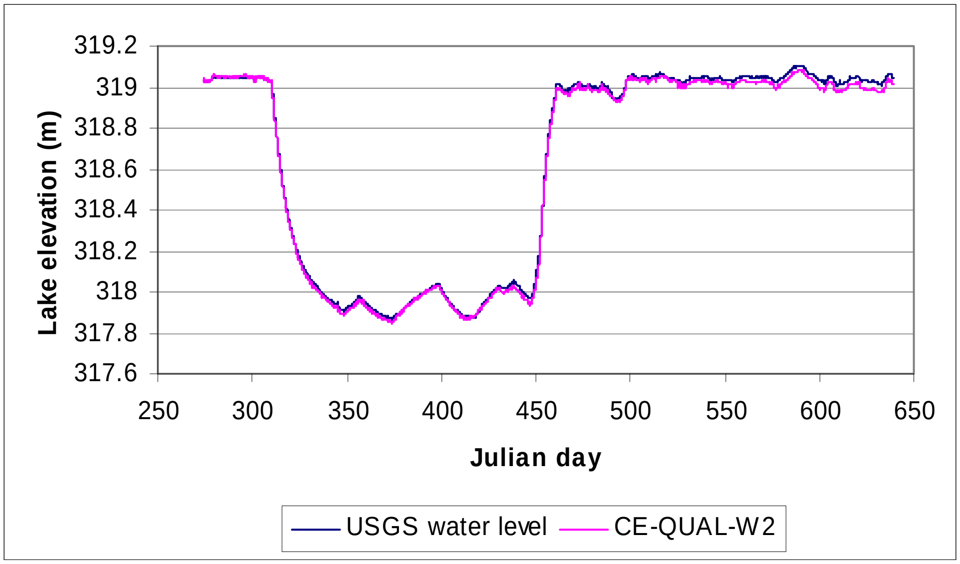


Figure 40. Moses Lake CE-QUAL-W2 water level results compared to Moses Lake USGS water level data from October 2000 to September 2001.

Water Quality Boundary Conditions

Water quality boundary conditions were assessed for each of the hydrologic inflows/outflows to Moses Lake. These included Rocky Ford Creek, Crab Creek, and Rocky Coulee Wasteway (described in above sections) as well as groundwater inputs and lake outlets. Groundwater water quality was assessed by samples drawn from mini-piezometers driven into the lake sediments near the shore (Pitz, 2003). The south outlet of Moses Lake was sampled routinely throughout the study period to measure the outflow of constituents.

Initial Conditions

The initial conditions of Moses Lake for the calibration year were determined by Ecology's first intensive lake assessment in March 2001. Prior sampling was not possible because of low lake levels and ice covering. The lake was being filled at the time of the March sampling with feed water; however, this only affected a small portion of the lake at the time. The rest of the lake was well mixed, and a single initial value for each parameter was used to characterize the initial conditions. The initial condition of some parameters in the upper part of the Rocky Ford Arm may have been under-estimated initially; however, the initial values have less importance as the lake equilibrates quickly with the relative large hydrologic input from the boundaries.

Model Water Quality Calibration

One lake survey per month provided the measured field data for calibration. Calibration was accomplished by adjustment of model coefficients during successive or iterative model runs, until optimum goodness of fit between the model results and observed field values was achieved. Goodness of fit was measured using the root mean squared error (RMSE), a commonly used measure of model variability (Reckhow et al., 1986). The RMSE is defined as the mean of the squared difference between the measured and simulated values. It is similar to a standard deviation of the error. All model coefficients were adjusted within acceptable ranges as described by Cole and Wells (2002), Chapra (1997), EPA (1985), and EPA (1987).

Water Temperature

Water temperature affects the rates of chemical and biological reactions as well as determines the solubility of oxygen in water. The heat budget which determines the water temperature is based on physical processes which can be accurately modeled by CE-QUAL-W2. The water temperatures in Moses Lake were accurately simulated with an overall RMSE of 0.67 ºC (CV = 4%; n = 263). Figures 41 to 46 present a comparison of simulated and measured water temperatures at each sampling station.

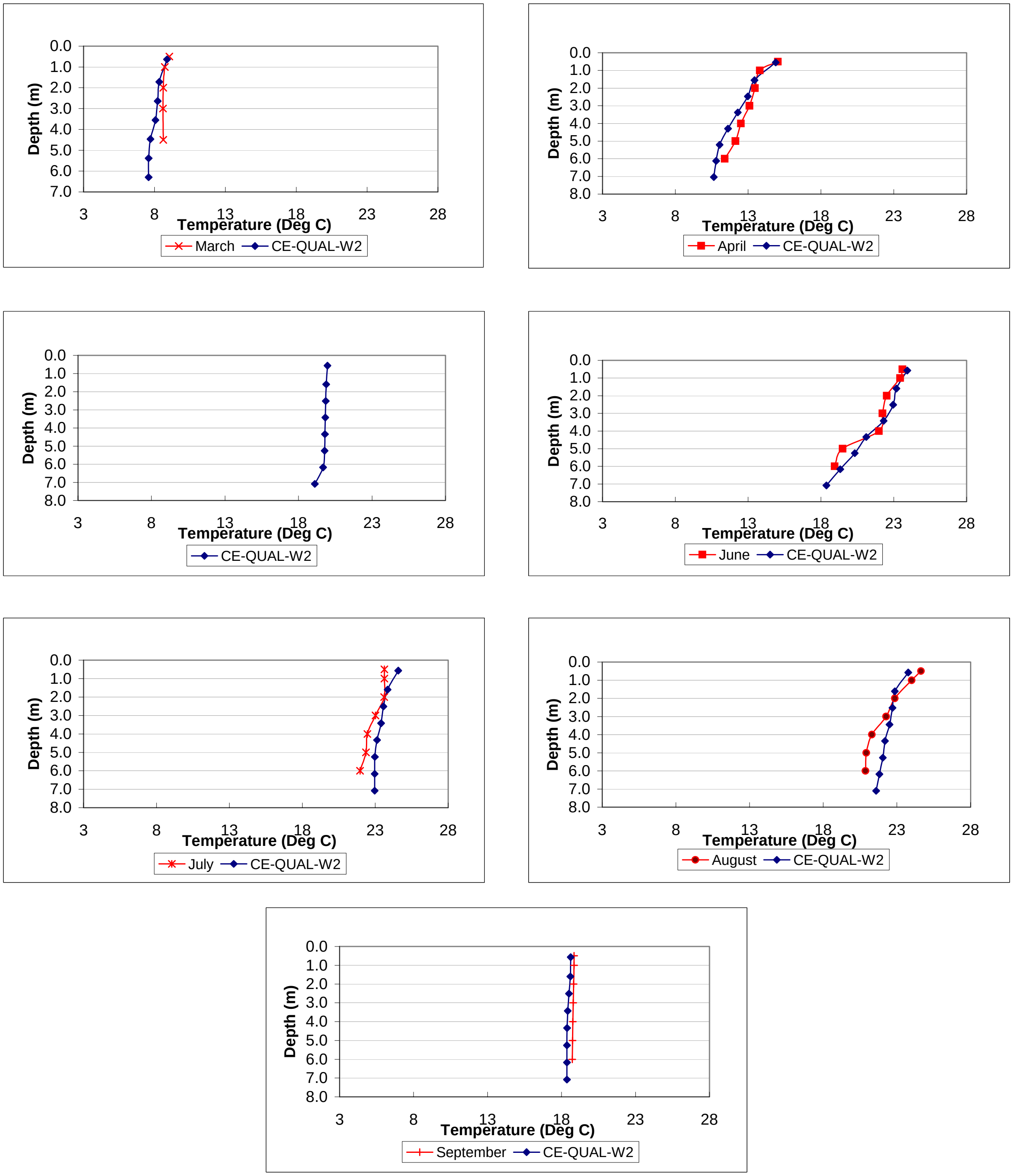


Figure 41. Comparison of model-predicted vertical temperature profiles with 2001 data for Moses Lake station ML-1.

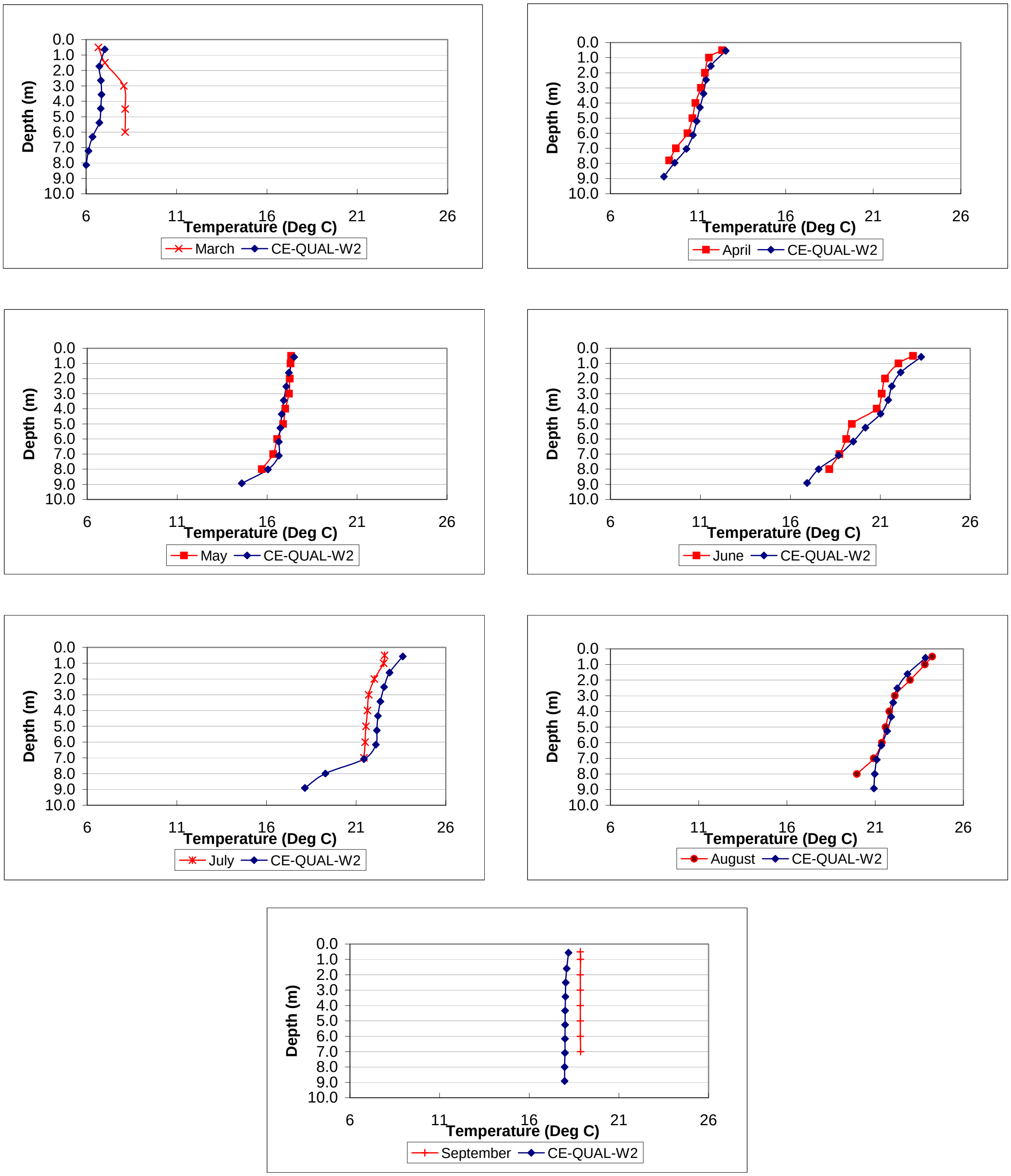


Figure 42. Comparison of model-predicted vertical temperature profiles with 2001 data for Moses Lake station ML-2.

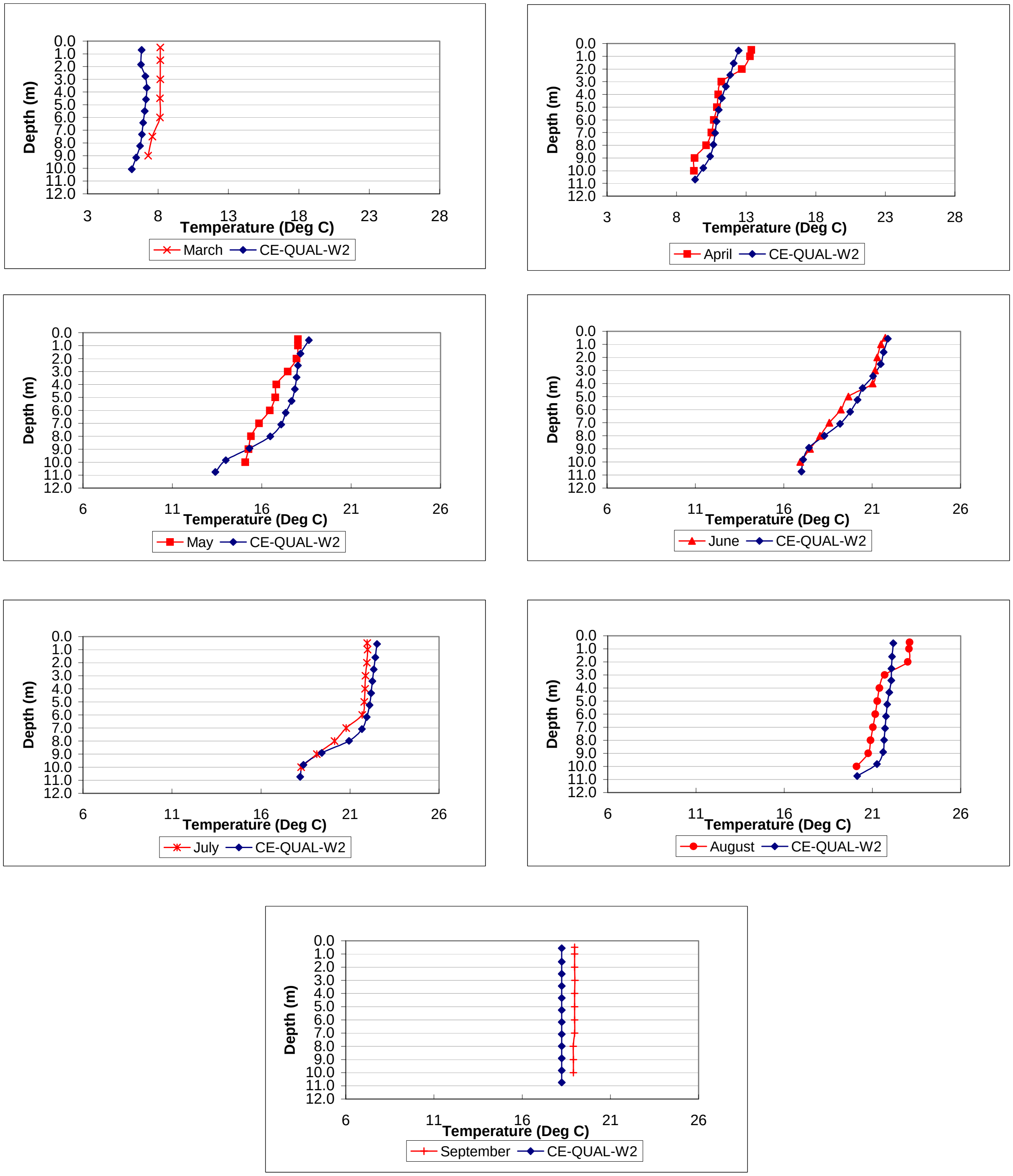


Figure 43. Comparison of model-predicted vertical temperature profiles with 2001 data for Moses Lake station ML-3.

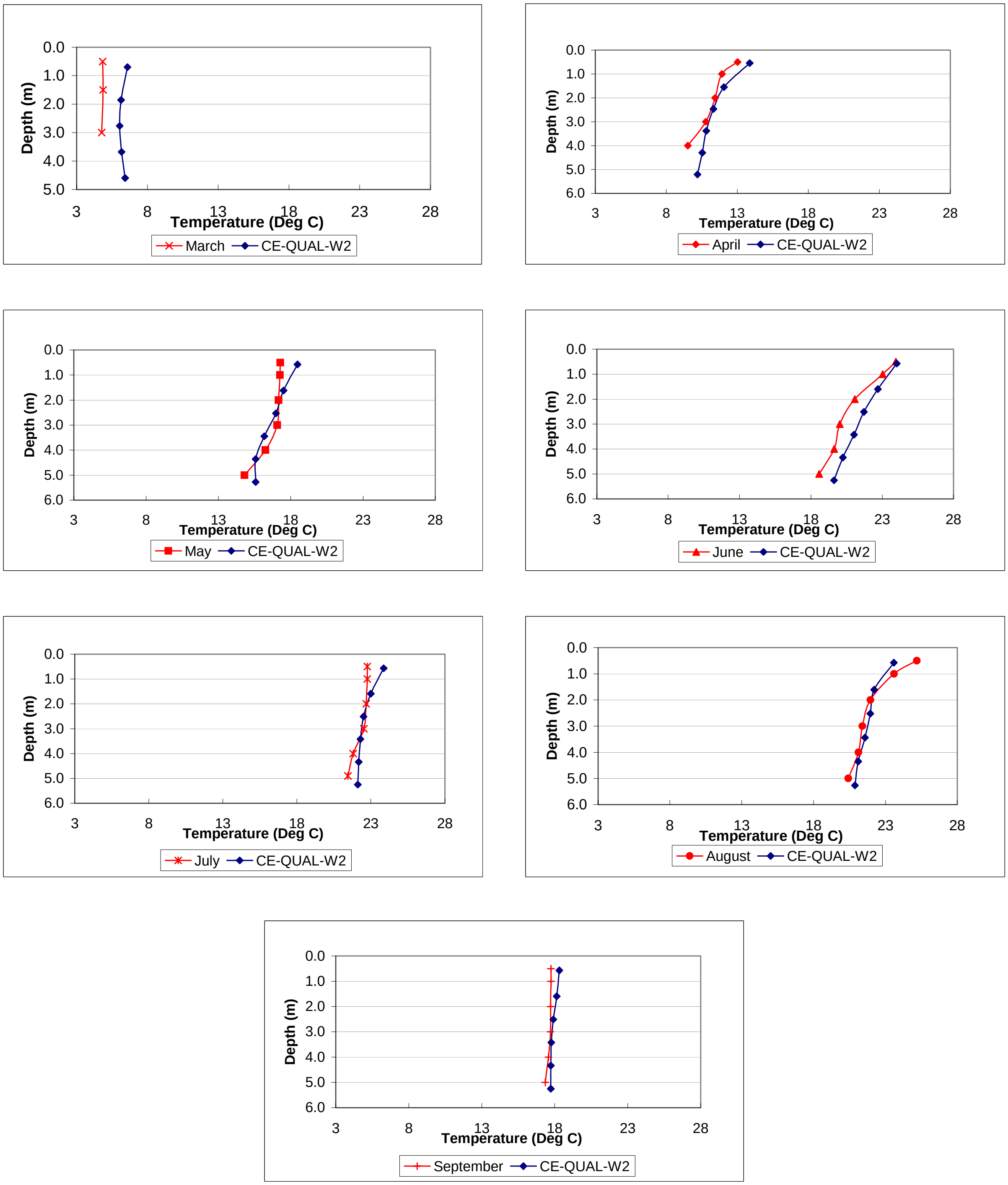


Figure 44. Comparison of model-predicted vertical temperature profiles with 2001 data for Moses Lake station ML-4.

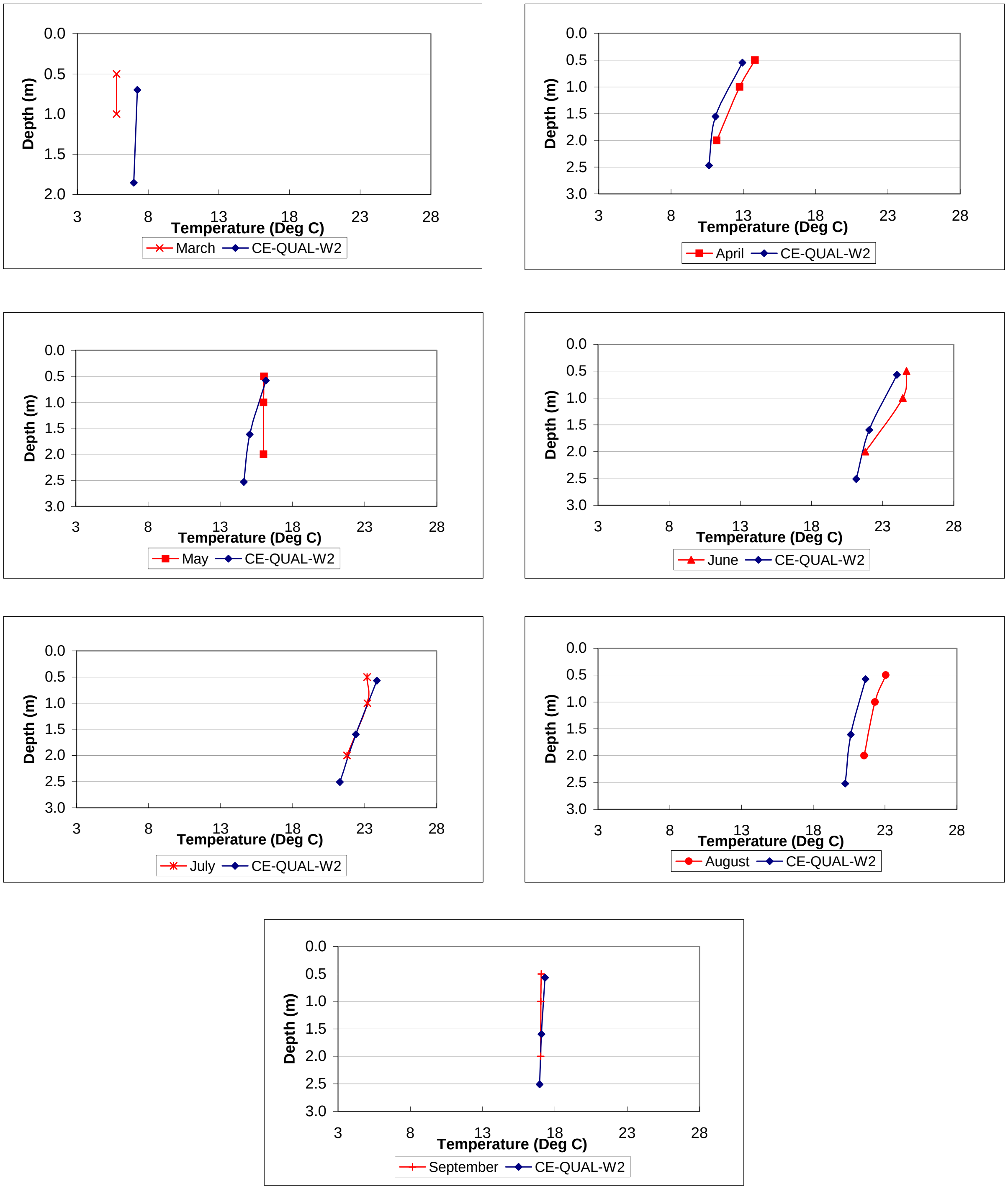


Figure 45. Comparison of model-predicted vertical temperature profiles with 2001 data for Moses Lake station ML-5.

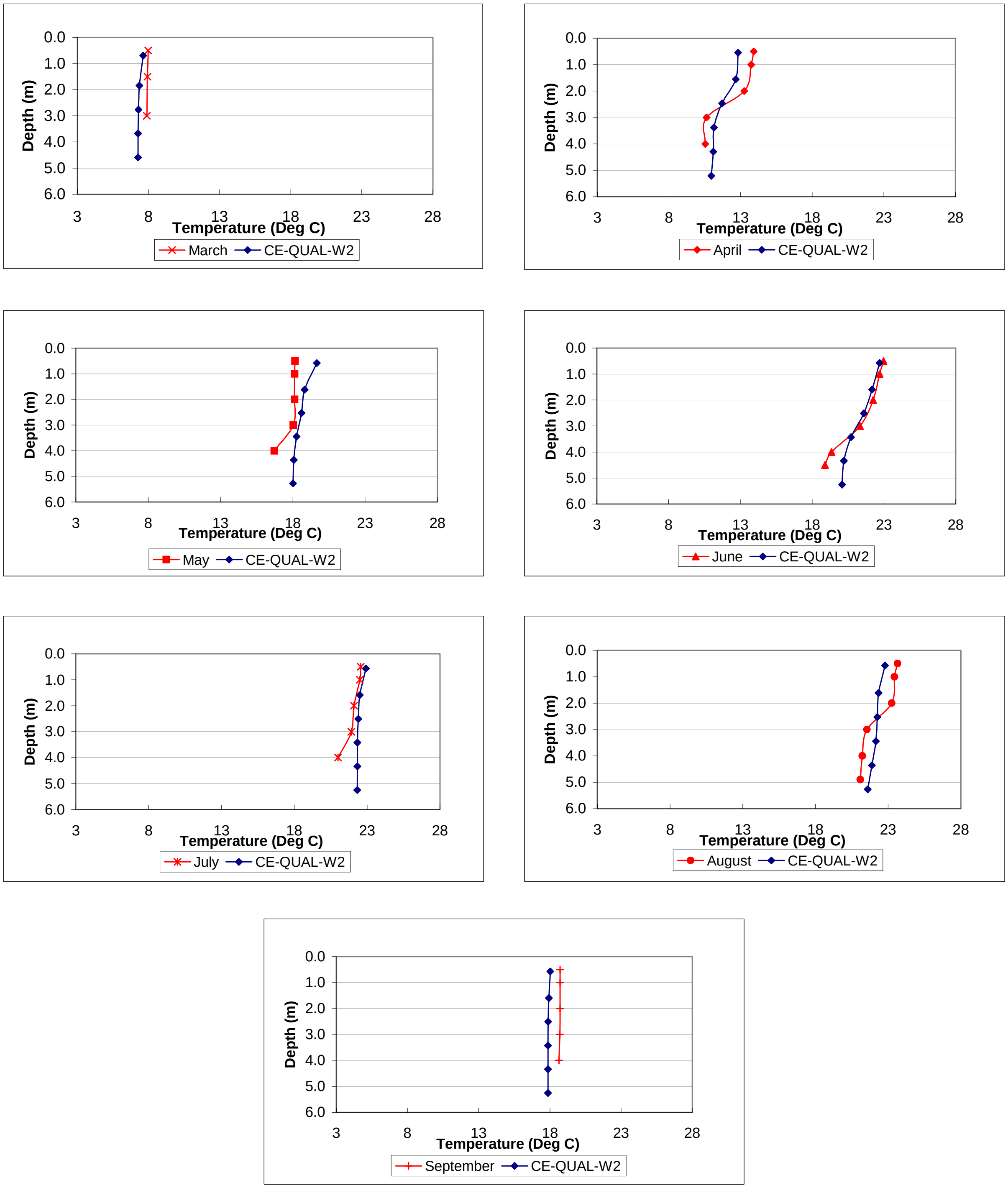


Figure 46. Comparison of model-predicted vertical temperature profiles with 2001 data for Moses Lake station ML-6.

Conservative Tracer: chloride

Chloride was simulated in CE-QUAL-W2 as a conservative tracer. A conservative tracer provides a good diagnostic check to see if the model is missing any substantial sources or sinks of water. This is particularly useful when the incoming sink or source concentration is greatly different (higher or lower) from the ambient concentration, as is often the case for groundwater. Geometric mean chloride concentrations of inflowing groundwater varied from 7.8 mg/L in Rocky Ford Arm to 26.2 mg/L in Pelican Horn for 2001. Conversely, the average chloride concentration of feed water (Columbia River water) was approximately 1.0 mg/L. Simulating the mixing of these different strengths of chloride is also a good test of the accuracy of the CE-QUAL-W2 transport processes of advection and dispersion.

Figures 47 to 52 show a comparison of measured and simulated chloride concentrations for Moses Lake. The model showed good agreement with an overall RMSE of 0.57 mg/L (CV = 14%; n = 108). In 2001, conductivity which has often been used in Moses Lake as a conservative tracer was not found to be conservative. A substantial source of conductivity associated with anoxic sediment release of ions to the overlying water caused the CE-QUAL-W2 model to consistently under-predict conductivity, particularly when this higher conductivity water was entrained to upper waters during mixing events. Based on the 2001 data, conductivity is not a suitable conservative tracer for Moses Lake.

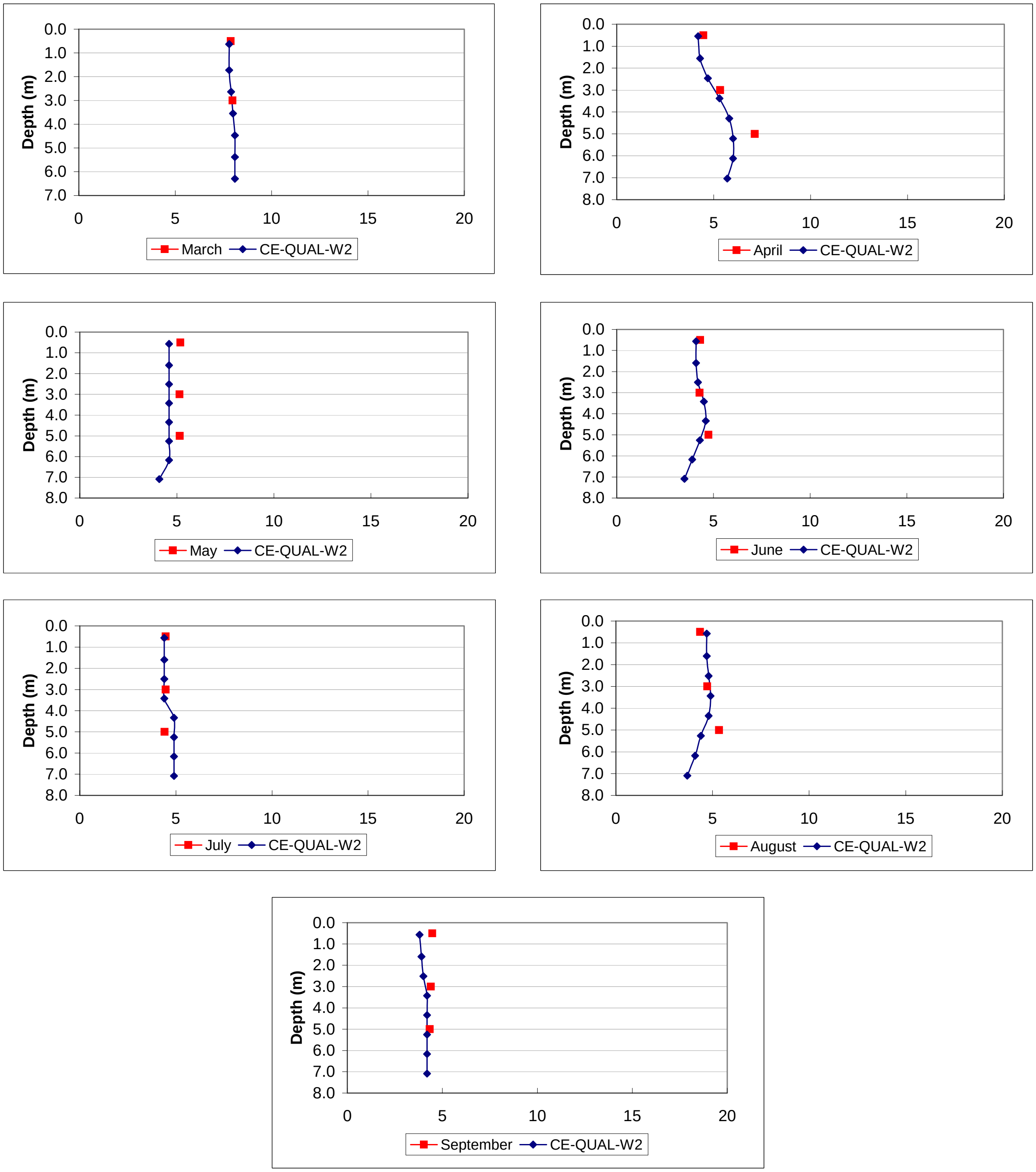


Figure 47. Comparison of model-predicted vertical chloride profiles with 2001 data (mg/L) for Moses Lake station ML-1.

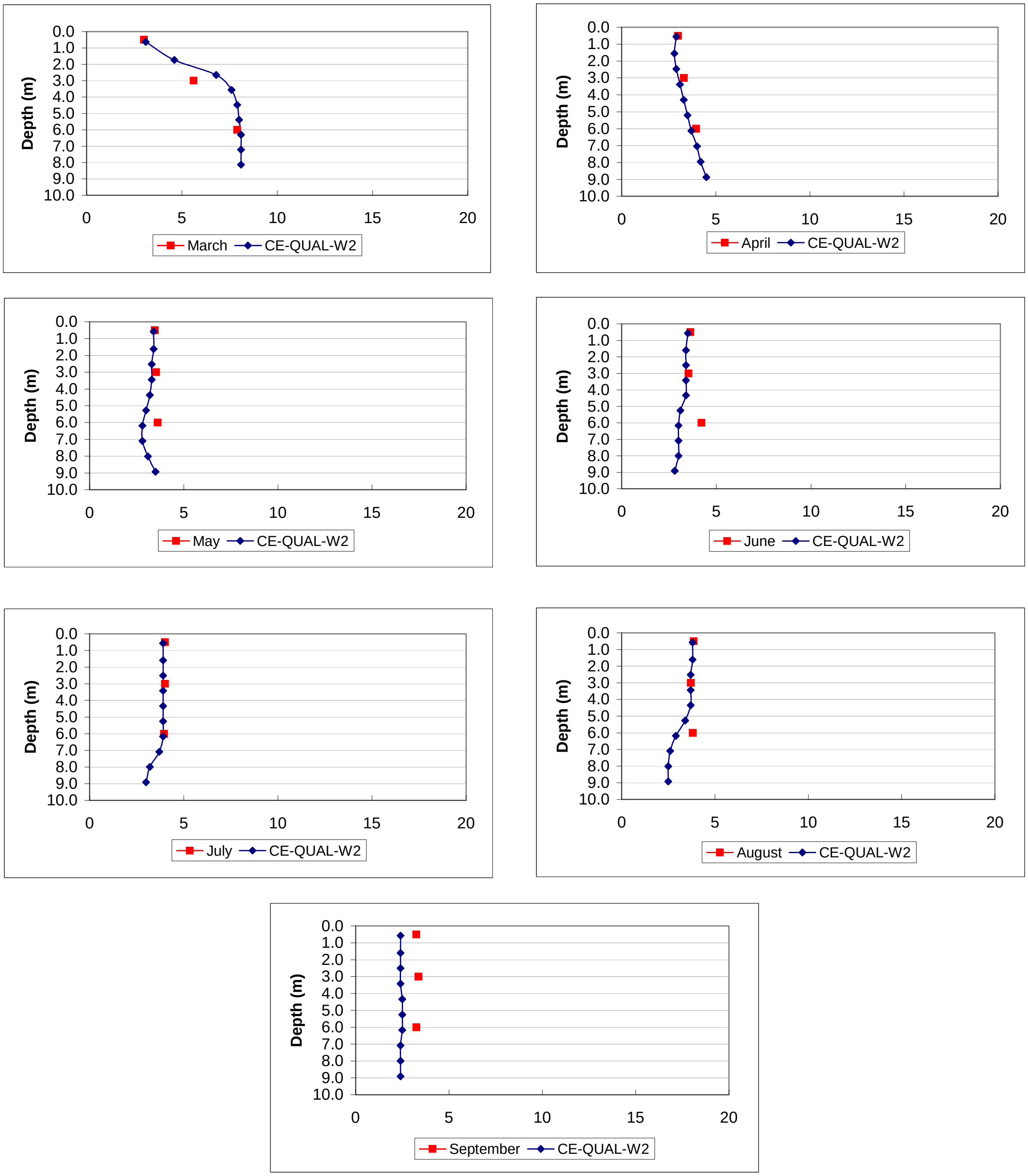


Figure 48. Comparison of model-predicted vertical chloride profiles with 2001 data (mg/L) for Moses Lake station ML-2.

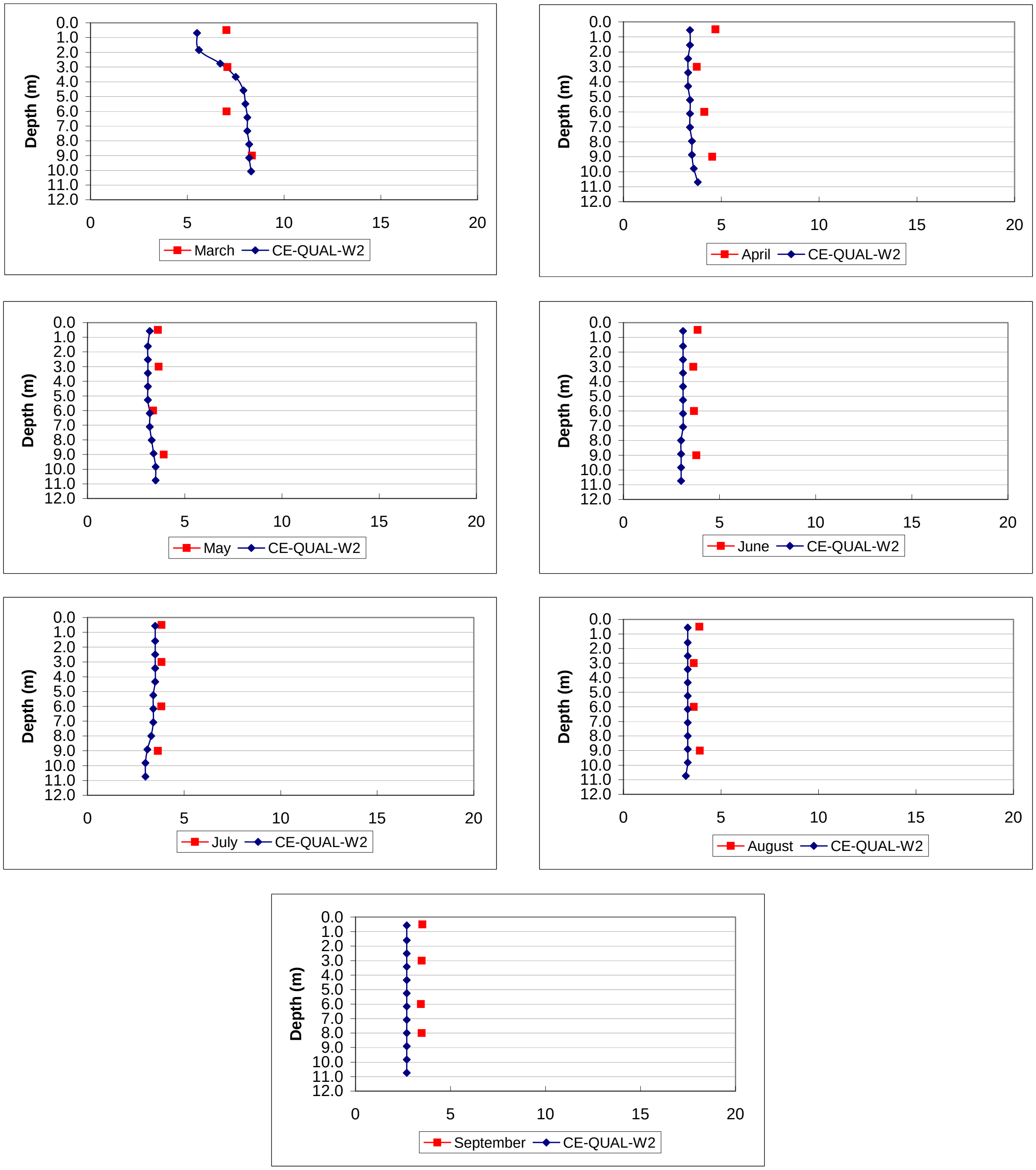


Figure 49. Comparison of model-predicted vertical chloride profiles with 2001 data (mg/L) for Moses Lake station ML-3.

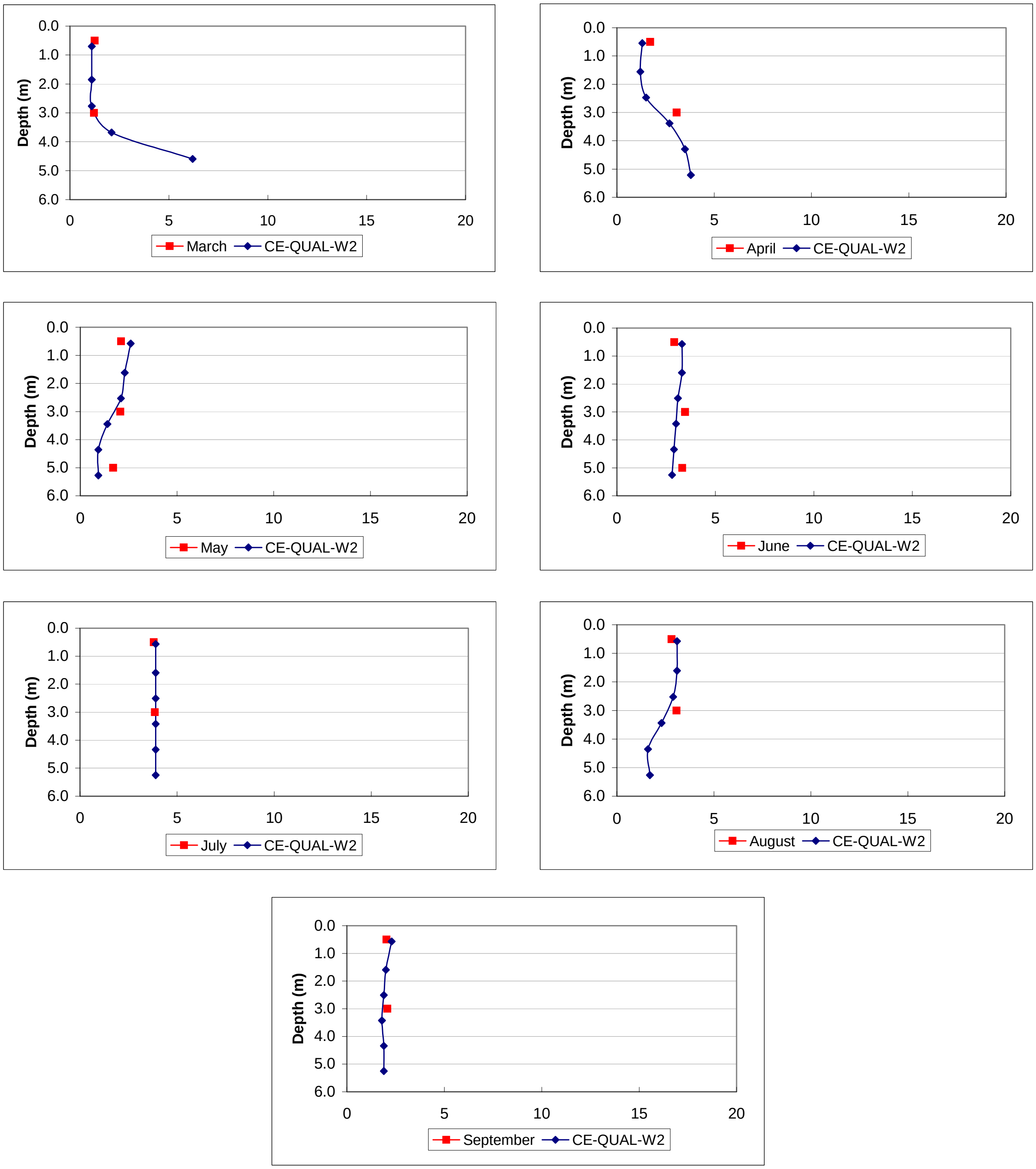


Figure 50. Comparison of model-predicted vertical chloride profiles with 2001 data (mg/L) for Moses Lake station ML-4.

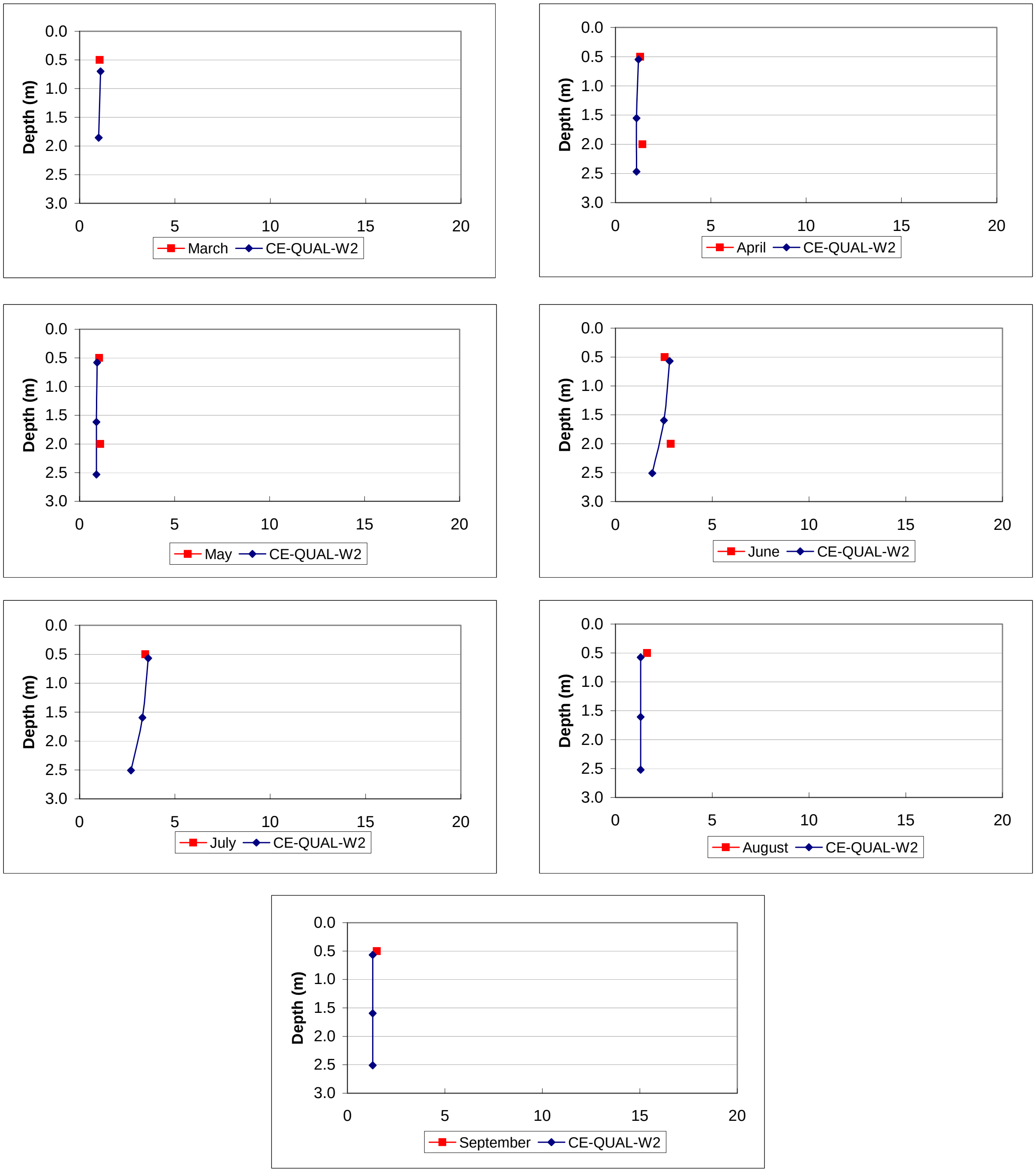


Figure 51. Comparison of model-predicted vertical chloride profiles with 2001 data (mg/L) for Moses Lake station ML-5.

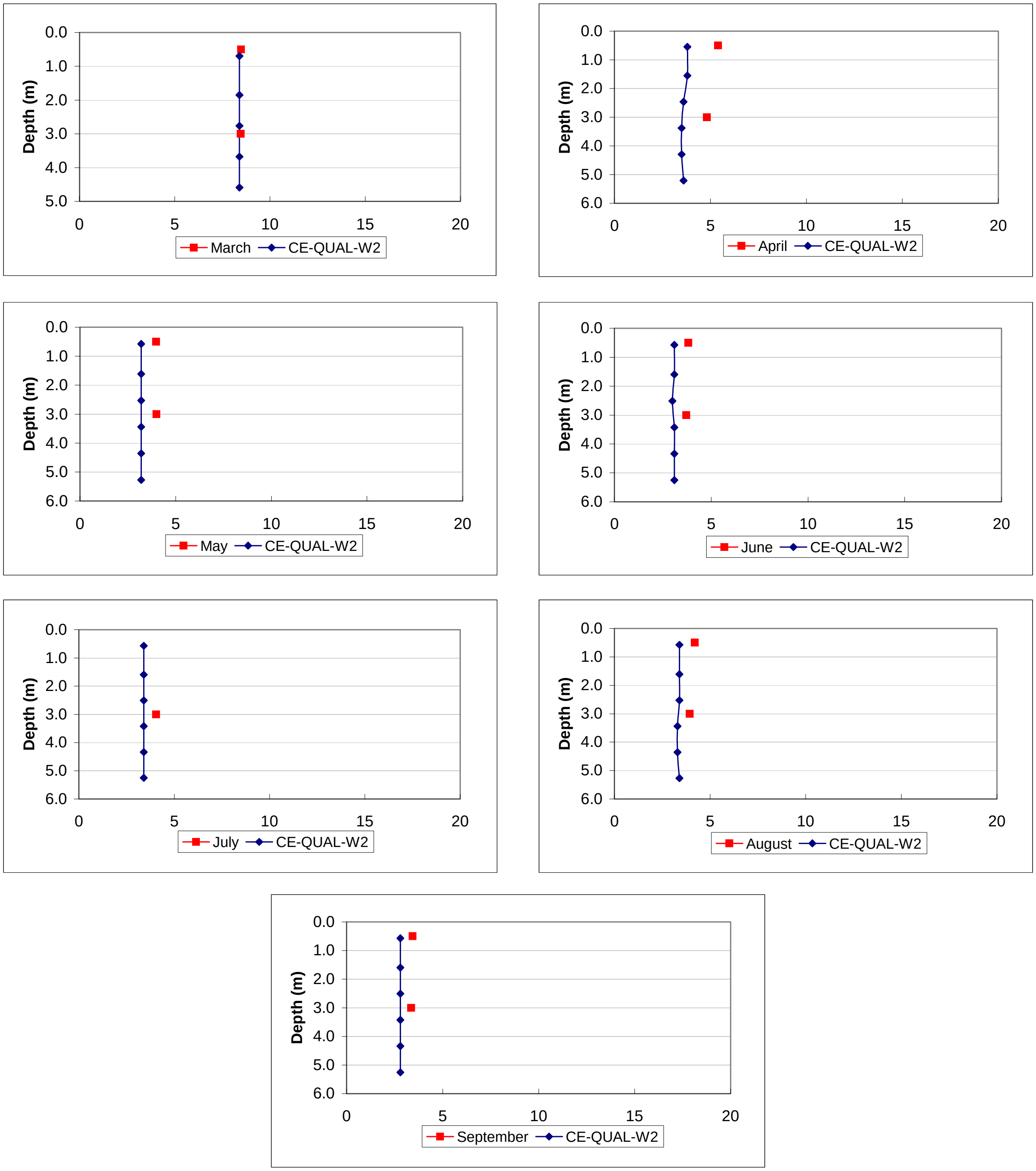


Figure 52. Comparison of model-predicted vertical chloride profiles with 2001 data (mg/L) for Moses Lake station ML-6.

Total Phosphorus

CE-QUAL-W2 simulates TP as the summation of phosphorus in ortho-P, algae, and dissolved and particulate organic matter. The concentration of TP in the water column is therefore unaffected by algal uptake and respiration, and decomposition processes of organic matter. The mass is conserved in those processes. The processes that do affect TP include settling, sediment release/resuspension, and boundary inflows/outflows. The calibrated model of Moses Lake simulated TP reasonably well, with an overall RMSE of 14 ug/L TP (n=107) throughout the water column for all sampling sites (Table 12). The total %RSD for TP measurements was approximately 10% or 5 ug/L at a concentration of 50 ug/L.

Table 12. Summary of error statistics for the 2001 calibration of TP. Spacial, temporal, and overall error expressed as RMSE (mg/L).

	ML5	ML4	ML3	ML1	ML2	ML6	*Total*
March	0.003	0.001	0.007	0.005	0.005	0.011	0.007
April	0.005	0.006	0.005	0.008	0.006	0.006	0.006
May	0.007	0.005	0.042	0.005	0.015	0.005	0.023
June	0.004	0.010	0.007	0.007	0.009	0.008	0.008
July	0.014	0.004	0.012	0.016	0.014	0.006	0.012
August	0.005	0.013	0.029	0.016	0.015	0.007	0.019
September	0.012	0.014	0.011	0.015	0.013	0.005	0.012
							Overall
Mar-Sept	0.007	0.009	0.021	0.012	0.012	0.007	0.014

The model simulated TP very well in some parts of Moses Lake, particularly Parker Horn (stations ML-4 and ML-5) and Pelican Horn (station ML-6) with seasonal RMSEs under 9 ug/L. Figures 53 to 58 present a comparison of model-predicted vertical TP profiles and the 2001 TP data for Moses Lake from March to September.

Much of the variability in the overall RMSE is the result of the model's under-prediction of a distinct increase in water column TP concentrations during May in the deeper basin stations of ML-2 and ML-3. This was most likely associated with a substantial increase in pH throughout the whole water column in late April and early May. Sediment release of phosphorus, even in aerobic waters, is possible with increases in pH above 8.0. The sediment release rate of phosphorus at a pH of 9.0 may be ten times greater than at a pH of 8.0 (Bostrom et al., 1982). Both basins had an increase in pH (>9.0) throughout the water column, resulting from the large vernal diatom bloom. CE-QUAL-W2 does not have an algorithm to model this type of phosphorus release.

The TP load leaving through the north and south outlets was assessed using the continuous discharge records (described above) and the simulated outflow TP concentrations. Simulated outflow TP concentrations were compared to measured outflow TP concentrations and had an overall RMSE of 9 ug/L (CV = 42%; n=8) for May through September.

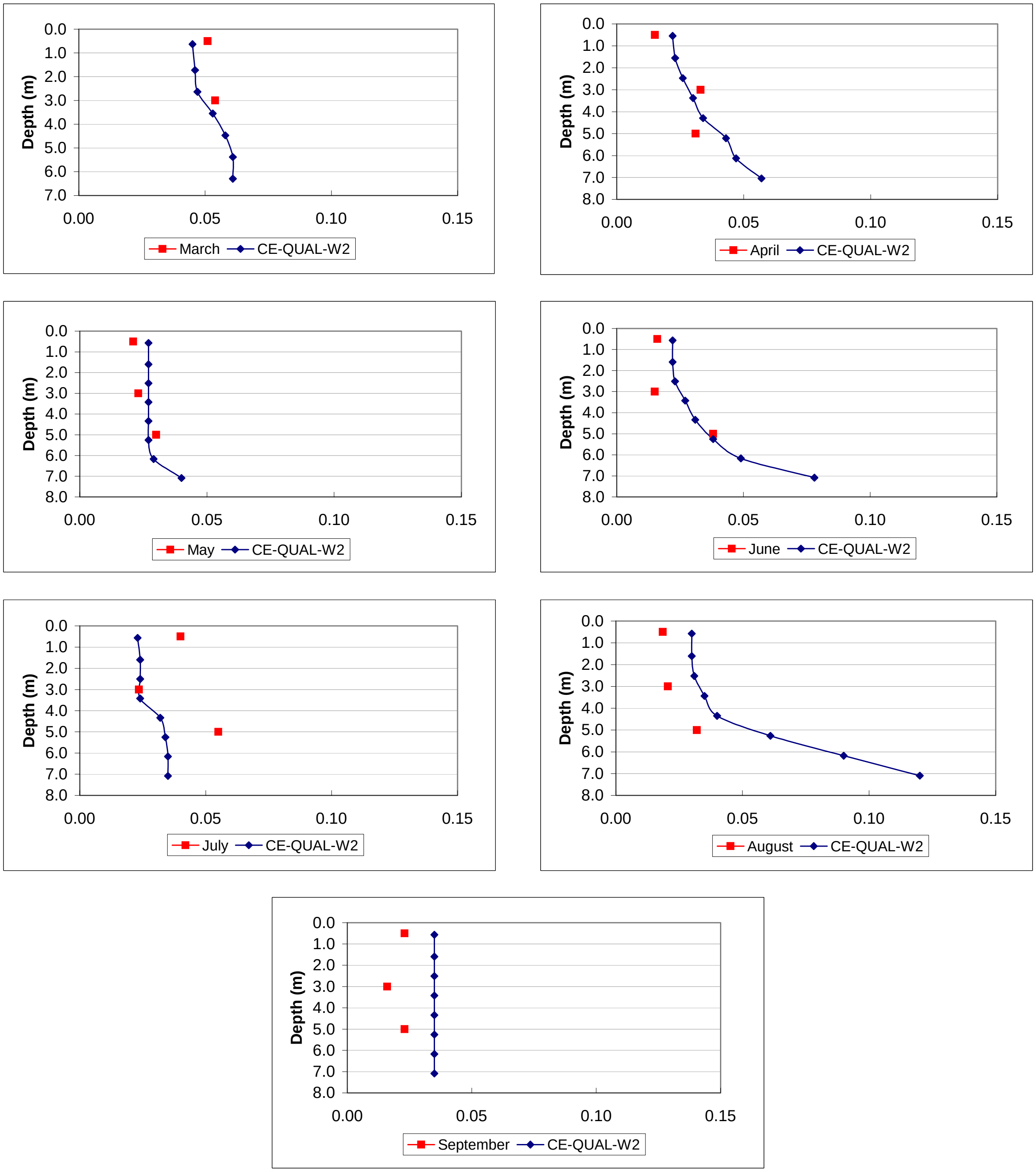


Figure 53. Comparison of model-predicted vertical TP profiles with 2001 data for Moses Lake station ML-1. (TP in mg/L)

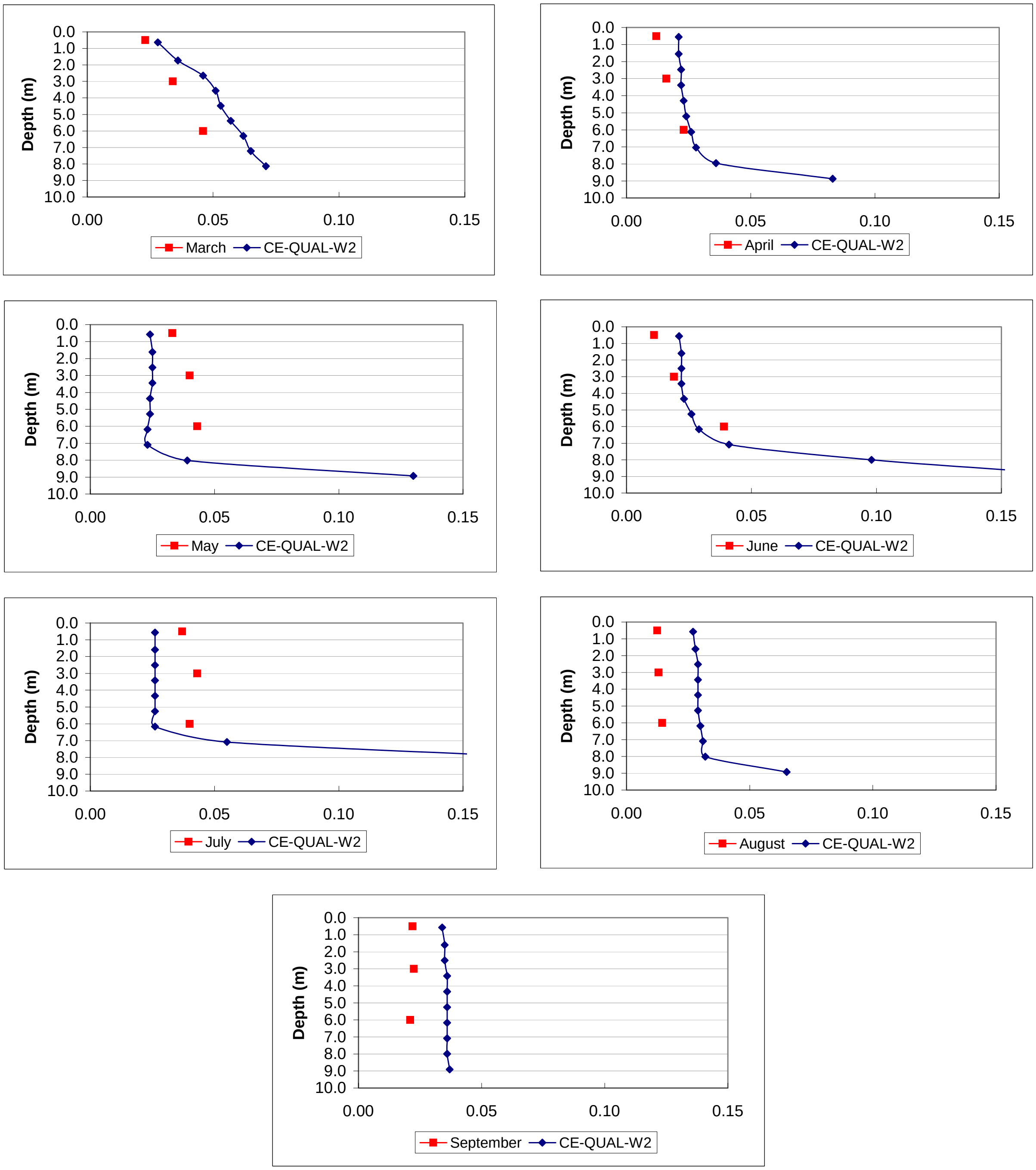


Figure 54. Comparison of model-predicted vertical TP profiles with 2001 data for Moses Lake station ML-2. (TP in mg/L)

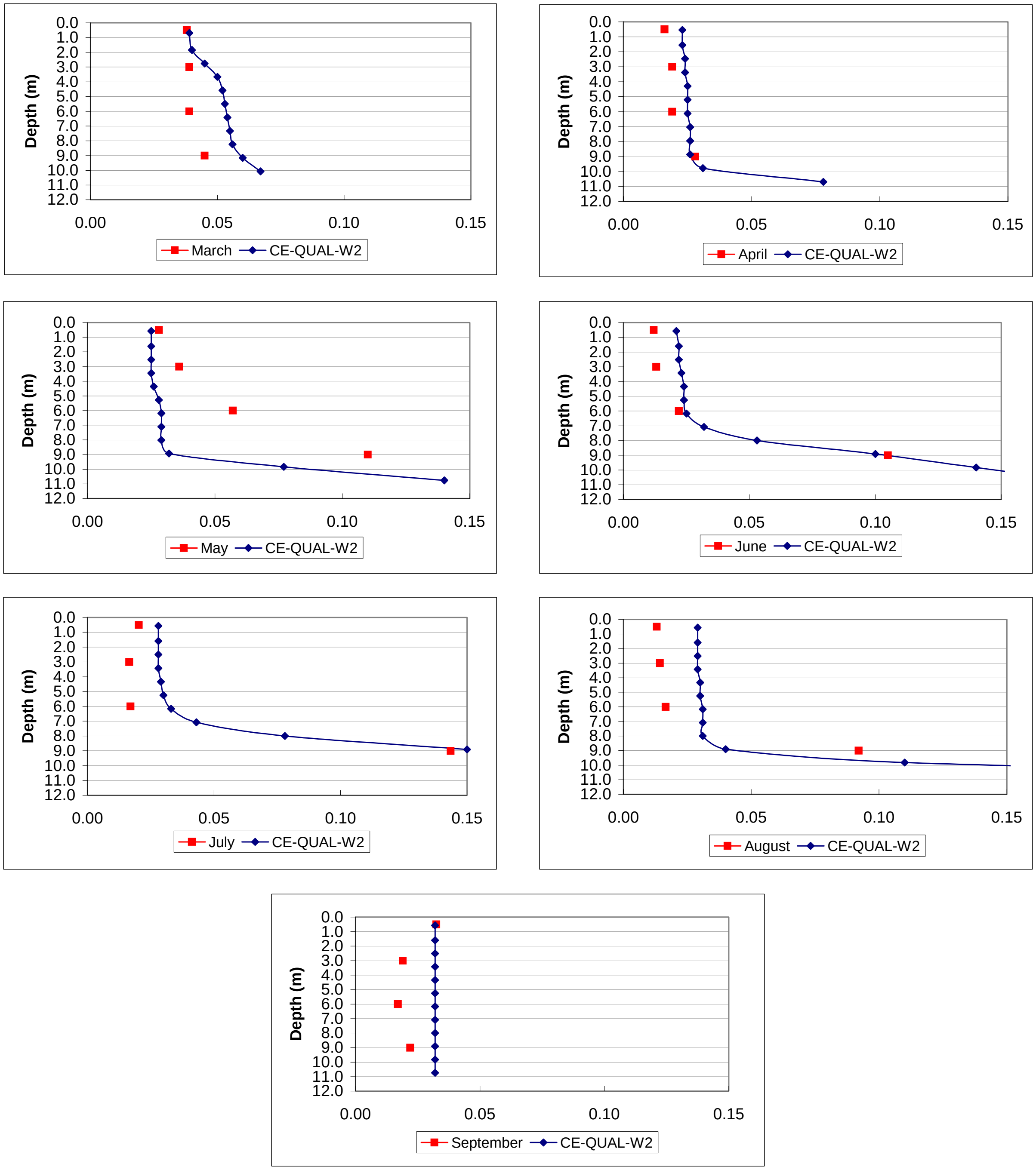
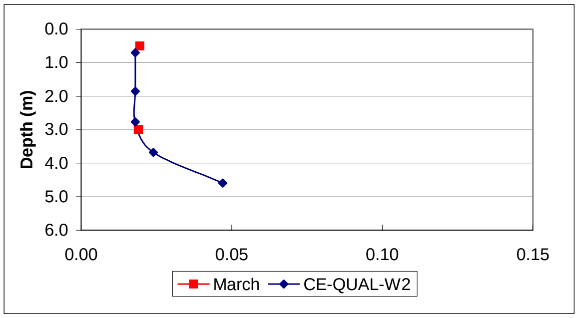
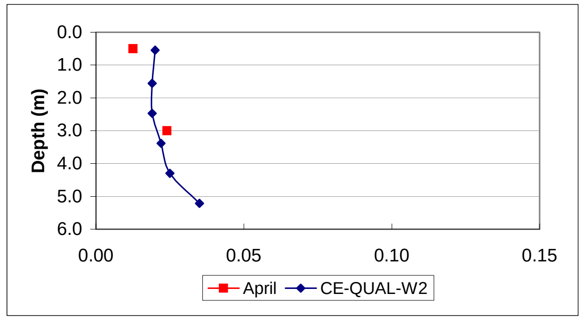
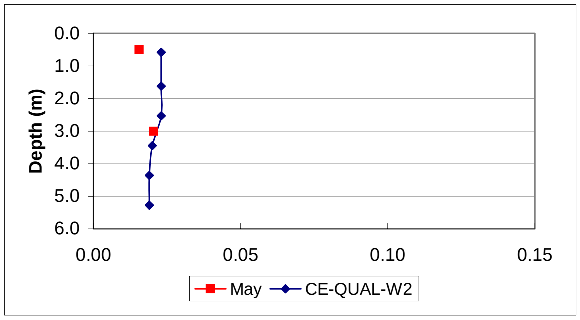
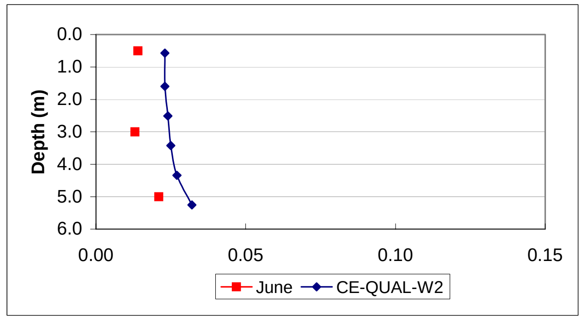


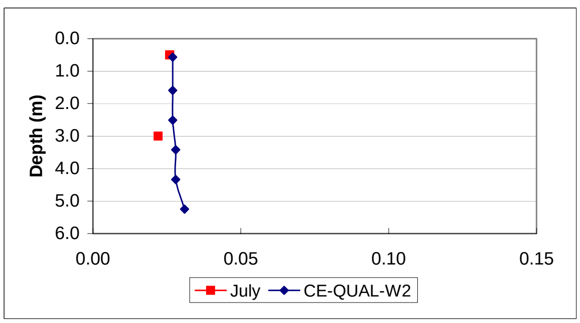
Figure 55. Comparison of model-predicted vertical TP profiles with 2001 data for Moses Lake station ML-3. (TP in mg/L)

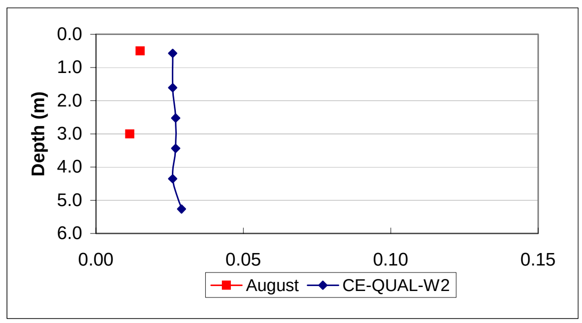












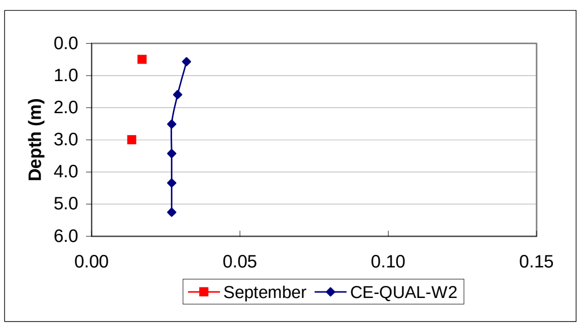


Figure 56. Comparison of model-predicted vertical TP profiles with 2001 data for Moses Lake station ML-4. (TP in mg/L)

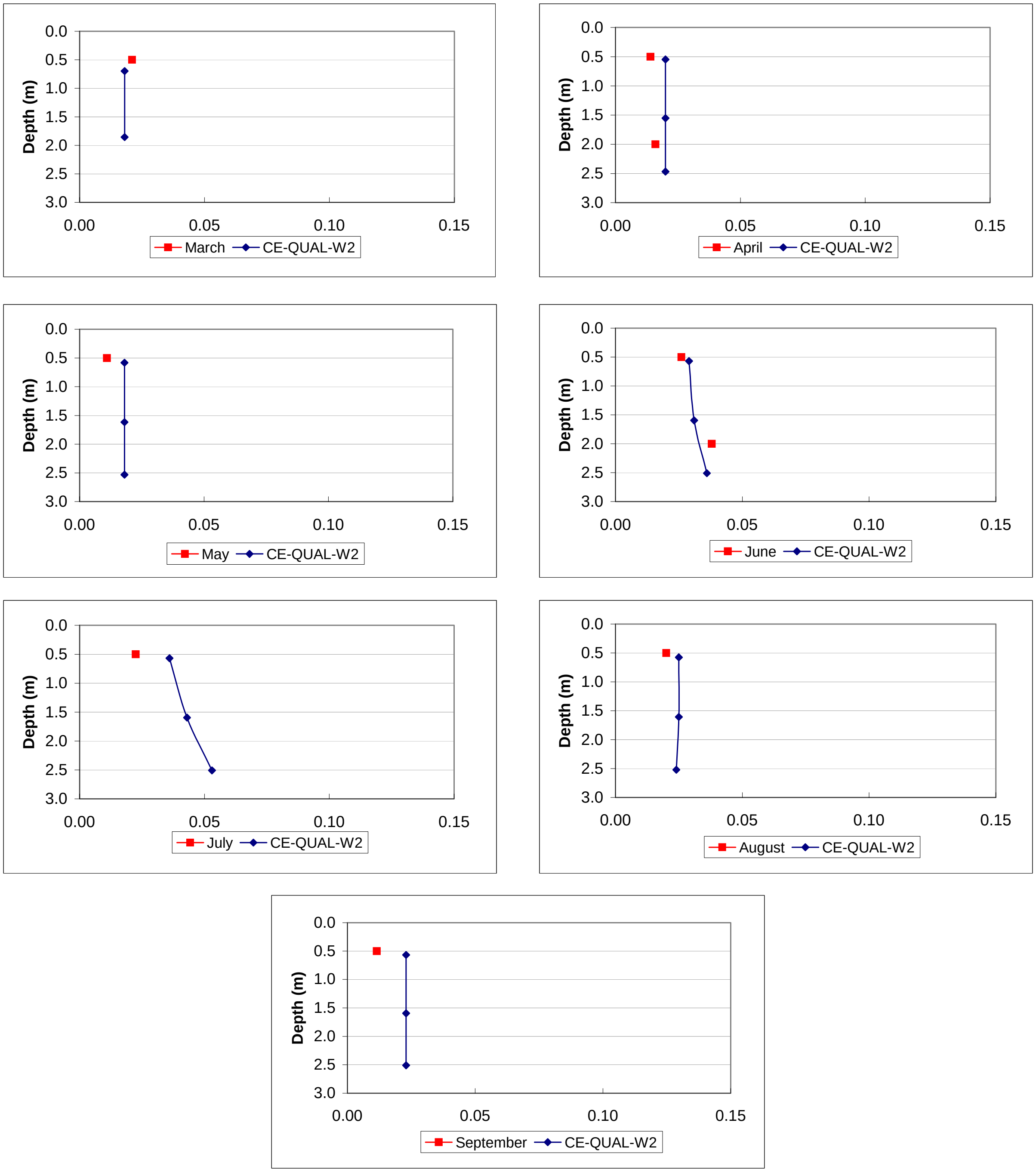


Figure 57. Comparison of model-predicted vertical TP profiles with 2001 data for Moses Lake station ML-5. (TP in mg/L)

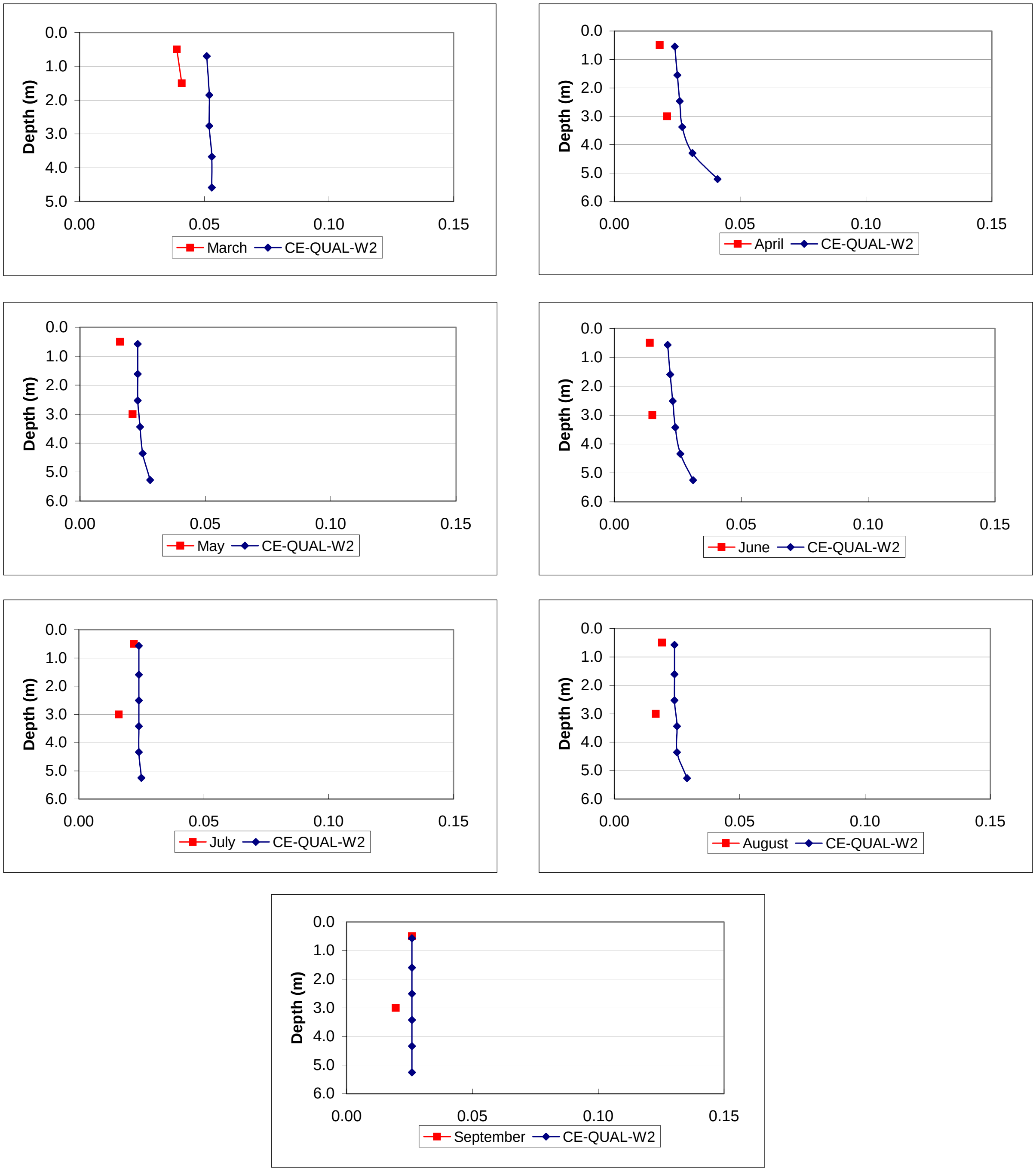


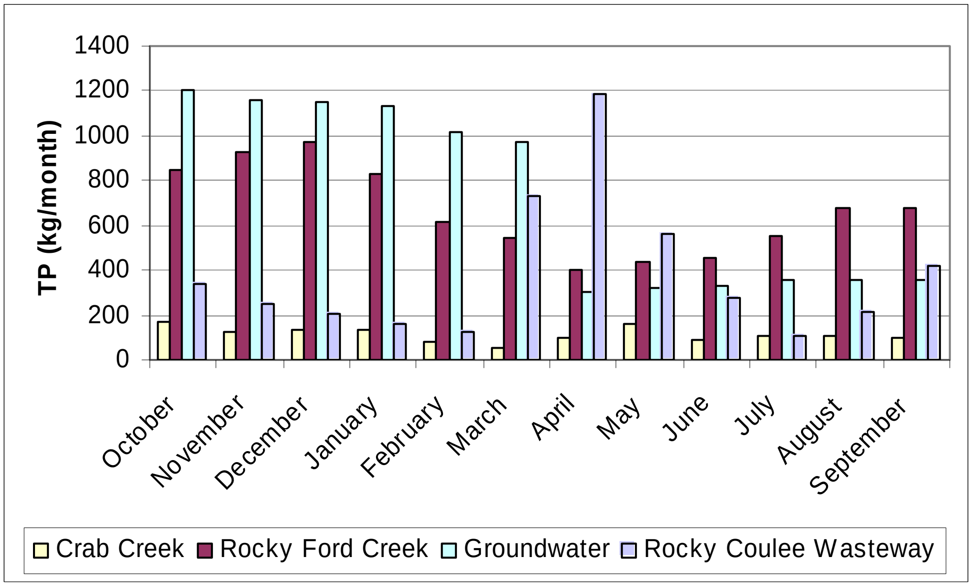
Figure 58. Comparison of model-predicted vertical TP profiles with 2001 data for Moses Lake station ML-6. (TP in mg/L)

2001 Phosphorus Budget

External TP Loading to Moses Lake

Figure 59 presents the monthly TP and ortho-P loads to Moses Lake from Crab Creek, Rocky Ford Creek, groundwater, and Rocky Coulee Wasteway. A total of 22,500 kg of TP (of which 16,677 kg was dissolved ortho-P) were discharged to Moses Lake from these four external sources. The majority of the TP load to the lake came from Rocky Ford Creek and groundwater, though Rocky Coulee Wasteway contributed a large TP load in April, May, and June associated with the large amount of feed water during that period. A large fraction (74%) of the TP load was in the dissolved ortho-P phase. Accordingly, the load contribution of ortho-P to Moses Lake was dominated by groundwater and Rocky Ford Creek throughout the year as well. The fraction of total load contribution (expressed as a percentage) from various sources is shown for May through September in Figure 60.

Groundwater had a substantial influence on the TP load to Moses Lake, especially in the fall and winter. Patmont (1980) also found that groundwater flow entered Moses Lake primarily in the fall and winter, coincident with an increase in groundwater levels in the upper aquifer and the annual winter drawdown of Moses Lake.



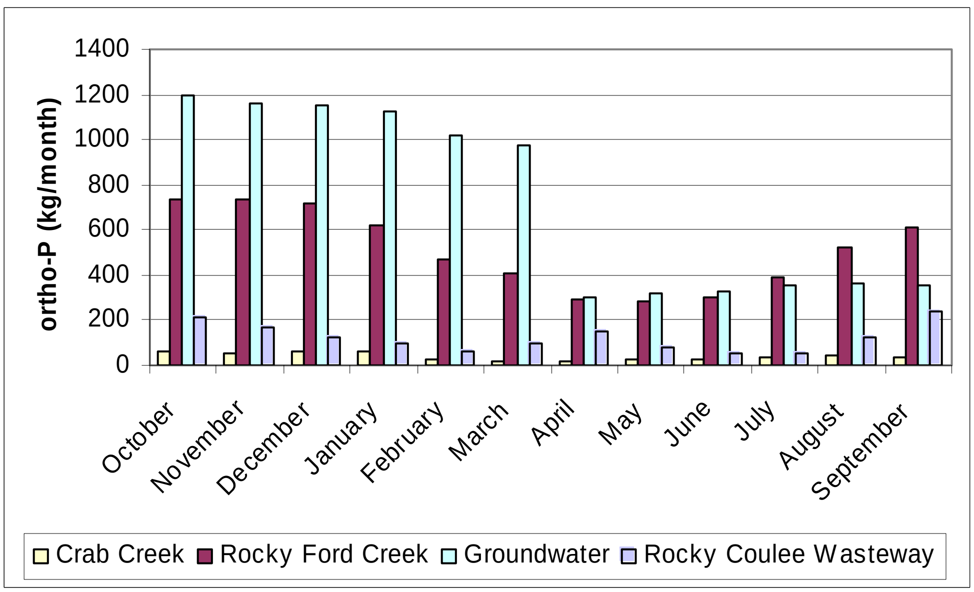


Figure 59. TP and ortho-P loadings from external sources during the 2000-01 study period.

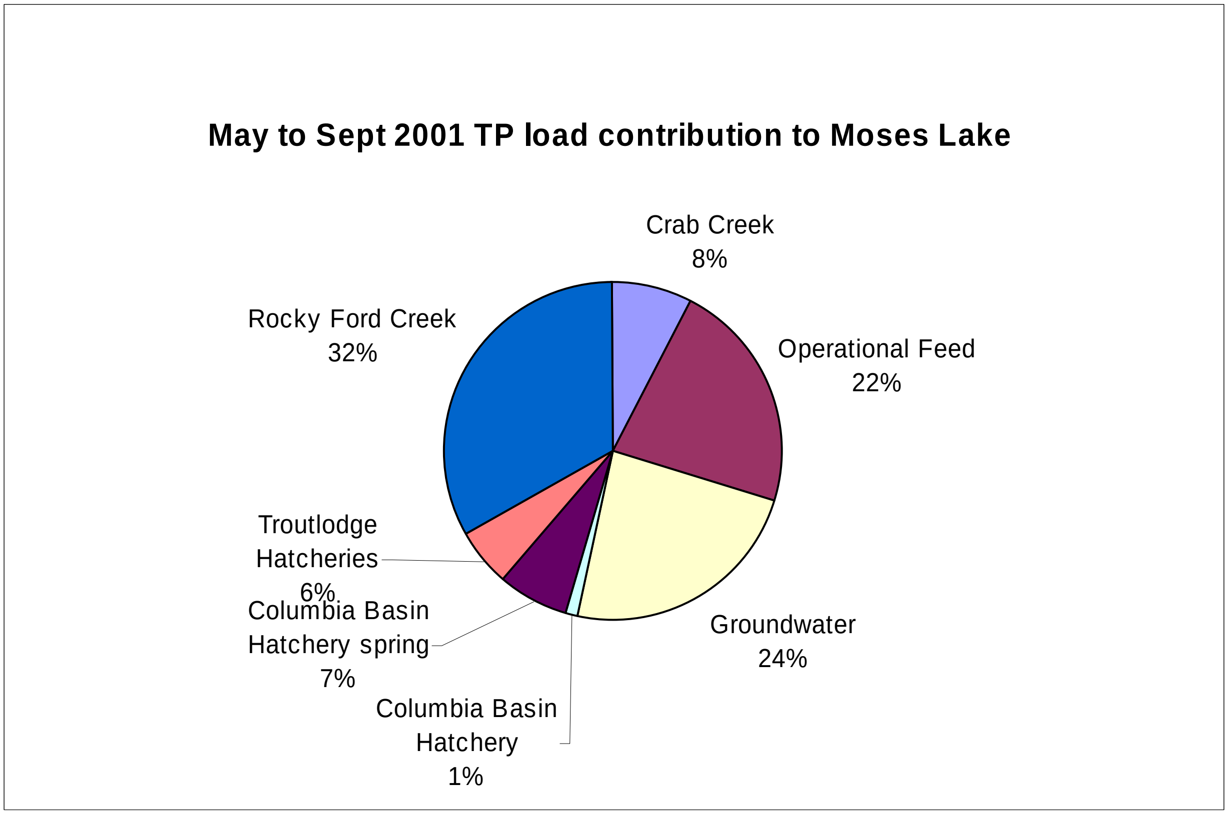


Figure 60. Percent contributions of the TP load to Moses Lake from external sources, May through September 2001.

Phosphorus Budget

The change in TP mass (storage) in Moses Lake was evaluated daily from the calibrated CE-QUAL-W2 model. A summary of CE-QUAL-W2 modeling results for TP from May through September 2001 are presented in Table 13. The outflow loads also were developed from the model. A summary of the monthly TP budget for March through September 2001 is presented in Table 14. Internal loading occurred from April through September as evidenced by the decreasing net settling losses or the net internal gains (as in July and August). There was a distinct decrease in net internal loading gain in 2001 compared to that in the historical phosphorus budgets of the 1980s.

Table 13. Summary of CE-QUAL-W2 modeling results for May through September 2001. All results are means for the specified time period.

	Branch 1 Parker Horn	Branch 2 South Basin	Branch 3 Lewis Horn	Branch 4 upper Rocky Ford Arm	Branch 4 lower Rocky Ford Arm	Branch 5,6,7,8 Pelican Horn	Whole Lake
May to September							
% dilution	46	32	45	13	28	28	27
TP concentration in whole column (ug/L)	**30**	**40**	**25**	**40**	**40**	**26**	**38**
TP concentration below 6m (ug/L)	60	64	0	54	76	33	69
TP concentration above 6m (ug/L)	24	26	25	40	28	26	30
TP mass in whole column (kg)	335	1004	54	1138	1971	282	4796
TP mass below 6m (kg)	69	572	0	67	944	4	1654
% TP mass below 6m	21%	57%	0%	6%	48%	2%	34%
% Volume below 6m	10%	35%	0%	4%	25%		
% increase to [TP] by including <6m	26%	51%	0%	2%	44%	0%	24%
May							
% dilution	55	42	59	21	38	36	36
TP concentration in whole column (ug/L)	**27**	**31**	**25**	**37**	**31**	**24**	**31**
TP concentration below 6m (ug/L)	43	41	0	36	47	29	44
TP concentration above 6m (ug/L)	23	16	25	35	19	24	28
TP mass in whole column (kg)	300	772	53	1032	1507	265	3947
TP mass below 6m (kg)	49	370	0	45	585	4	1052
% TP mass below 6m	16%	48%	0%	4%	39%	1%	27%
% Volume below 6m	10%	35%	0%	4%	25%		
% increase to [TP] by including <6m	19%	92%	0%	5%	63%	0%	11%
June							
% dilution	48	37	46	17	33	32	31
TP concentration in whole column (ug/L)	**28**	**34**	**24**	**39**	**35**	**25**	**34**
TP concentration below 6m (ug/L)	47	50	0	48	61	28	55
TP concentration above 6m (ug/L)	23	16	24	37	20	25	29
TP mass in whole column (kg)	306	855	51	1101	1743	276	4349
TP mass below 6m (kg)	53	448	0	61	756	4	1319
% TP mass below 6m	17%	52%	0%	6%	43%	1%	30%
% Volume below 6m	10%	35%	0%	4%	25%		
% increase to [TP] by including <6m	21%	110%	0%	6%	76%	0%	17%
July							
% dilution	29	25	26	11	21	21	19
TP concentration in whole column (ug/L)	**34**	**47**	**26**	**37**	**43**	**25**	**40**
TP concentration below 6m (ug/L)	94	95	0	68	106	40	99
TP concentration above 6m (ug/L)	24	14	26	34	17	24	26
TP mass in whole column (kg)	375	1204	56	1040	2142	269	5096
TP mass below 6m (kg)	108	842	0	85	1318	5	2357
% TP mass below 6m	29%	70%	0%	8%	62%	2%	46%
% Volume below 6m	10%	35%	0%	4%	25%		
% increase to [TP] by including <6m	41%	233%	0%	9%	160%	1%	51%
August							
% dilution	34	19	30	6	15	19	17
TP concentration in whole column (ug/L)	**34**	**51**	**26**	**41**	**49**	**27**	**44**
TP concentration below 6m (ug/L)	82	95	0	70	116	37	104
TP concentration above 6m (ug/L)	25	18	26	38	20	27	31
TP mass in whole column (kg)	375	1308	57	1159	2448	299	5658
TP mass below 6m (kg)	94	846	0	87	1448	5	2476
% TP mass below 6m	25%	65%	0%	8%	59%	2%	44%
% Volume below 6m	10%	35%	0%	4%	25%		
% increase to [TP] by including <6m	33%	183%	0%	8%	145%	0%	45%
September							
% dilution	65	35	66	9	35	33	33
TP concentration in whole column (ug/L)	**29**	**35**	**25**	**49**	**41**	**27**	**39**
TP concentration below 6m (ug/L)	33	38	0	46	48	30	44
TP concentration above 6m (ug/L)	25	21	25	47	28	27	38
TP mass in whole column (kg)	315	873	54	1363	2009	299	4920
TP mass below 6m (kg)	38	341	0	58	599	4	1040
% TP mass below 6m	12%	39%	0%	4%	30%	1%	21%
% Volume below 6m	10%	35%	0%	4%	25%		
% increase to [TP] by including <6m	14%	64%	0%	4%	42%	0%	3%

Table 14. Summary of the monthly TP budget for March through September 2001. (load in kg)

Month	Outflows	Inflows				Change in storage	Net internal load/settling
		Ground-water	Rocky Ford Creek	Crab Creek	Rocky Coulee Wasteway		
March	1466	971	545	54	644	-1696	-2444
April	2479	304	406	92	1251	-1292	-866
May	890	320	437	160	561	268	-321
June	670	328	452	90	298	426	-72
July	210	358	550	105	111	1163	250
Aug	1304	360	672	104	209	-226	-267
Sept	2076	354	697	100	427	-729	-232
May-Sept	5150	1720	2809	560	1606	901	-643

Other Phosphorus Sources

Other phosphorus sources not specifically allocated as seasonal phosphorus loads in this TMDL evaluation are stormwater runoff (overland flow and unknown contributions from City of Moses Lake stormwater collection system), waterfowl contributions (more than 50,000 waterfowl winter on Moses Lake each year), and net pen fish production (the state Department of Fish and Wildlife operates a facility from October to March in the South basin).

Many of these sources probably have a minimum impact during the critical season of May through September because they take place mostly in the winter. Any phosphorus loads that enter Moses Lake in the winter become part of the initial conditions for the critical season. The Moses Lake CE-QUAL-W2 model was calibrated using measured initial conditions from March 2001. These initial conditions include the sum impacts of all winter phosphorus loading including stormwater runoff, waterfowl feces, and net pen fish. Soluble phosphorus in the water column initially fuels the spring diatom bloom or is washed out as the lake is filled up in the spring. Particulate phosphorus that enters Moses Lake in the winter either breaks down into soluble phosphorus, settles to the bottom sediments, or is washed out of Moses Lake. Any effects that phosphorus in the sediments may have from May through September are contained in the residual of the phosphorus mass balance as the internal phosphorus load term (i.e., release of phosphorus from the sediments during anoxic conditions in the summer). The Moses Lake CE-QUAL-W2 model incorporates a phosphorus-sediment release algorithm to account for the internal phosphorus load and was calibrated to the 2001 hypolimnion phosphorus data.

Even though Moses Lake receives minimal precipitation from May through September, summer thunderstorms can occur that may create non-point phosphorus loading from runoff. Lake-shore runoff can include fertilizers, pet feces, oils, and soil among other contaminants. These could lead to temporary phosphorus spikes in the Moses Lake water column and should be included in a BMP evaluation for Moses Lake.

TMDL Assessment

Applicable Water Quality Criteria

Carroll et al. (2000) reviewed historical water quality studies on Moses Lake and, based on the historical review, presented an evaluation of nutrient criteria for Moses Lake. In summary, the following was established:

- Water (natural and imported) in the Columbia Basin is managed for irrigation and flood control by the Columbia Basin Irrigation Project (CBIP). Since the 1950s, CBIP management has permanently altered the hydrologic regime of the watershed to the point where there is no historical reference condition for comparison.

- Subsequent extensive study and restoration done on Moses Lake since the inception of the CBIP determined excessive phosphorus loading as the source of impairment to Moses Lake, with the impairment being the excessive blue-green algae blooms which affect the characteristic uses of recreational and aesthetic enjoyment during the summer months.

- Total nitrogen was recommended to be delisted from the 303(d) list, and future lake management activities and decisions focus on the control of TP to manage the blue-green algal biomass in Moses Lake.

- Halting accelerated hypereutrophic conditions and restoring Moses Lake to a pre-impacted condition would most likely result in a continued eutrophic state, with associated characteristic uses of a productive lake.

- Characteristic uses for eutrophic north temperate lakes are reduced aesthetic properties, reduced water contact recreation, and productive warm-water fisheries. In general, these reflect the current and historical characteristic uses and conditions of Moses Lake, and suggest a level of protection and management for Moses Lake.

- Management of Moses Lake for other than a eutrophic condition was deemed impracticable, and has not been the focus or objective of rehabilitation measures to date.

- A link between TP concentration and an endpoint indicator, chlorophyll *a* concentration, was established in historical studies. Based on historical management recommendations, it was proposed that a maximum concentration of 50 ug/L TP would limit chlorophyll *a* concentrations to an endpoint target of 20 ug/L during the growing season (May- September). The endpoint target of 20 ug/L chlorophyll a maximum concentration would substantially reduce the likelihood of hypereutrophic conditions (excessive blue-green algae biomass) in Moses Lake.

- Ecology proposed adopting the established 50 ug/L TP criterion to develop a TMDL for Moses Lake. Based on available knowledge, the 50 ug/L TP criterion seemed to protect the characteristic lake uses, have a basis in the historical lake restoration efforts, be an achievable target, and probably be best reflected the historical development of Moses Lake.

- The proposed 50 ug/L TP criterion exceeds the action value of 35 ug/L TP established in Washington State water quality standards for lakes in the Columbia Basin ecoregion.

EPA (2001) has recently published information to support the development of state nutrient criteria for lakes and reservoirs in the xeric west ecoregion, of which Moses Lake is a part. EPA recommended a summer season reference condition and criterion of 35 ug/L of TP for the Moses Lake area sub-ecoregion. This criterion was empirically derived to represent lakes and reservoirs in this region that are minimally impacted by human activities and protective of aquatic life and recreational uses. EPA urges states to develop site-specific nutrient criteria, using the EPA reference condition for comparison.

Based on current knowledge (explained below), Ecology still recommends a maximum, mean in-lake TP criterion of 50 ug/L for Moses Lake during the May through September critical season. Load reductions necessary to achieve the 50 ug/L criterion throughout the lake were modeled.

Seasonal Variation and Impaired Uses

The goal of this TMDL is to manage and mitigate the excessive hypereutrophic blooms of blue-green algae that have occurred in Moses Lake since the inception of the CBIP. These blue-green algae blooms have been documented as impairing the beneficial uses of Moses Lake during the summer months. Welch et al. (1989) has documented that diatoms have typically dominated the spring populations (March and April) in Moses Lake, while the excessive blue-green algae blooms have occurred in May through September. For the purpose of this TMDL, May through September will be considered the critical season of concern for Moses Lake.

There are several factors that affect the biomass of algae during the critical season:

- The initial conditions of the lake at the start of the critical season.
- The exchange rate of water entering the lake through the critical season.
- The replenishment of nutrients to the lake during the critical season.
- The meteorological conditions during the critical season.

The initial conditions of Moses Lake in May are influenced by the percentage of natural runoff versus feed water that fills Moses Lake during its winter to summer stage transition. This mix first affects the extent and magnitude of the early spring diatom bloom (March and April) and then the algal assemblage of the May through September period.

The exchange rate of water during May through September will affect the algal biomass. Higher exchange rates occur when continued or additional feed water extend into this period. Exchange rates can be high enough to effectively dilute the nutrient concentrations in the lake (when using low-nutrient feed water) and, to some minimal extent, wash out algal cells. Higher exchange rates are associated with dry years when more feed water is needed to meet irrigation demand.

Lower exchange rates occur in wet years when Rocky Ford Creek and Crab Creek are the only surface water discharge to Moses Lake and irrigation demand is lower.

The replenishment of phosphorus, particularly ortho-P, to Moses Lake during May through September must occur to fuel the summer algal biomass development. The vernal diatom bloom will usually respond with enough intensity to deplete the initial bio-available phosphorus mass within the euphotic zone, so additional phosphorus sources are required. Disregarding internal loading of phosphorus (i.e., sediment release) and short-term recycling, the only other phosphorus replenishment comes from the tributary or groundwater inflows to Moses Lake. During wet years, summer flows in Rocky Ford Creek and Crab Creek (both which originate from groundwater) and direct groundwater inflows are higher. Thus, wet years are more likely to introduce higher replenishing loads of phosphorus throughout the summer than dry years when low-P feed water predominates the inflows.

Meteorological conditions (primarily wind) during the critical season will determine how much mixing will take place. High mixing (i.e., windy summer) will entrain the phosphorus released from sediments up into the euphotic zone where it can fuel algal biomass development. In a season with little mixing, the sediment-released phosphorus is trapped in the hypolimnion where it is not available for algal growth; however, there can be an aerobic release of sediment phosphorus to the epilimnion. In addition, hot summers with clear sunny weather will provide better growing conditions than cloudy, cool summers.

Loading Capacity Assessment

The nutrient target of 50 ug/L represents a whole-lake mean concentration. However, a whole-lake mean TP concentration is difficult and costly to ascertain. Traditionally, therefore, lake managers have relied on lake modeling to relate a whole-lake mean TP concentration to a certain amount of incoming TP load to the lake, which is easier to measure.

Carroll et al. (2000) suggested preliminary TP load allocations for Moses Lake based on applying the steady-state solution model of the mass balance equation to the annual flux of TP. While this was an effective solution for calculating load allocations, its shortfalls are that it assumes that the entire lake is mixed, that the entire lake has reached a steady state, and that phosphorus sedimentation/bottom release is uniform throughout Moses Lake. None of these conditions are true in Moses Lake every year.

Jones and Welch (1990) calibrated and verified three steady-state solution models for three separate sections of the lake, incorporating the variability of up to nine years of historical data. These models were relevant because they specifically modeled the critical season of concern (May through September) rather than annual conditions, and they had independent settling velocity coefficients for the three sections of the lake, but they did not address the whole lake or the loading interactions between the separate sections of the lake. Carroll et al. (2000) suggested that a hydrodynamic model capable of temporal and spatial analysis of TP fate and transport be developed to establish load allocations for Moses Lake.

The hydrodynamic CE-QUAL-W2 model of Moses Lake calibrated with the 2000-01 study period data was used to predict monthly mean in-lake TP concentrations from May through September during critical load conditions.

Design Criteria for Critical Load Conditions

- The season of concern is May through September when excessive blue-green algae blooms can occur. Evaluation of TP concentration compliance with the TP criterion was limited to this season.

- In order to develop an allocation strategy to improve Moses Lake's water quality, all of the major loading components to Moses Lake were characterized.

- The hydraulic conditions of 1980 were chosen to model critical flow conditions. The year represents an approximate 90th percentile flow for Rocky Ford Creek and Crab Creek and a 10th percentile flow for feed water through Rocky Coulee Wasteway (based on flow records from 1977-2001). The probability of these conditions occurring is approximately one in ten years on the average, which Ecology considers an acceptable exceedance probability (i.e., approximately 10%).

- The lake simulations began in mid-February. Initial phosphorus concentrations in the lake for all simulations were those used in the calibrated 2001 model. The 2001 data set was the most current depiction of initial conditions following the winter season and reflects current conditions. For instance, the initial conditions in Moses Lake prior to 1984 would reflect the discharge from the Moses Lake Wastewater Treatment Plant to Moses Lake.

- The year-to-year variation in TP concentration for Rocky Ford Creek varies little; its load depends more on variation in flow. Crab Creek was assumed to behave similarly during its predictable flow period from May through September. The CE-QUAL-W2 model uses ortho-P as a state variable, as part of TP. Most of Rocky Ford Creek's TP is ortho-P (75%). The long-term May through September ortho-P mean concentration of 106 ug/L was used as the initial starting concentration for a critical condition in Rocky Ford Creek. All of the groundwater phosphorus was considered to be ortho-P, and the 2001 concentration data were used for initial starting concentrations. The long-term May through September mean ortho-P concentration of 14 ug/L was used for starting concentrations in Crab Creek. Other phosphorus compartments for the critical load conditions, including that in algae and organic matter, were considered to be the same as the 2001 data set for all tributaries.

- The critical flow year (1980) had a winter/spring runoff flow from Crab Creek which began on February 24 at a flow rate of 12.3 cubic meters/second (cms), peaked on March 2 at 60.9 cms, declined rapidly to 10.5 cms by March 11, and then slowly declined to a baseflow of 2.0 cms by the end of April. For February 24 to March 11, an ortho-P concentration of 61 ug/L was used; this is the average ortho-P concentration from limited historical sampling of these events. Inorganic and organic matter concentrations were roughly tripled and doubled, respectively, from baseflow conditions for the high-flow period.

- Rocky Coulee Wasteway annual baseflow was estimated by Patmont (1980) to be 35 cfs. Annual loading was calculated using this baseflow and nutrient data collected from the 2000-01 study period. The baseflow was considered primarily spring-fed and thus assumed to be relatively constant throughout the year.

- Because Rocky Ford Creek and Crab Creek, which are groundwater driven, had an average increase of 30% for the critical seasonal flow compared to the 2001 seasonal flow, groundwater inflows were assessed to be 25% greater than the 2001 year inflows to account for a critical load groundwater flux.

- When evaluating model simulations, the entire water column TP was averaged for compliance with the TP criterion. Even though the algae grow in the euphotic zone, the entire water column was averaged because Moses Lake is polymictic (capable of mixing several times during the growing season). This avoided the complex task of trying to identify a critical meteorological conditions data set, by conservatively assuming any internal phosphorus loading is potentially available for algae growth. The 2001 year meteorology data were used for the simulation runs.

- Nutrient loading by atmospheric deposition and direct precipitation onto Moses Lake were not modeled. Both are considered negligible during the May through September critical season of concern, and any effects they may have are considered uncontrollable from a load reduction standpoint. In addition, any effects these loads might have are contained in the residual of the phosphorus mass balance and would be part of the terms controlling the internal loading process, in this case as phosphorus gain.

- In all assessments, the pump that conveys 50 cfs of water from Parker Horn to Pelican Horn was simulated as continuously running from April 2 through the end of September.

TMDL Findings and Allocations

Using the calibrated 2001 CE-QUAL-W2 model of Moses Lake, the critical load conditions were modeled in Moses Lake. A summary of the results for critical load conditions are presented in Table 15. Moses Lake was divided into different branches for analysis and comparison with the 50 ug/L criterion. The TP criterion was considered to be met when the May through September mean TP concentration was below the criterion in all the branches. For the critical load conditions, the mean TP concentration in the whole column was predicted to be 62 ug/L for May through September. The South Basin was predicted to have the highest seasonal monthly means ranging from 58 to 69 ug/L. The month of June was predicted to have the highest percentage (14%) of feed water in the whole lake, while the seasonal whole-lake average was predicted to be 8%. Figure 61 presents the percent contributions from external TP sources during critical load conditions.

Table 15. Summary of CE-QUAL-W2 modeling results for critical load conditions. All results are means for the specified time period.

	Branch 1 Parker Horn	Branch 2 South Basin	Branch 3 Lewis Horn	Branch 4 upper Rocky Ford Arm	Branch 4 lower Rocky Ford Arm	Branch 5,6,7,8 Pelican Horn	Whole Lake
May to September							
% dilution	19	9	22	3	8	7	8
TP concentration in whole column (ug/L)	**56**	**64**	**49**	**68**	**62**	**49**	**62**
TP concentration below 6m (ug/L)	98	98	0	82	112	57	105
TP concentration above 6m (ug/L)	48	49	49	68	51	49	55
TP mass in whole column (kg)	505	1471	80	1585	2765	399	6811
TP mass below 6m (kg)	68	667	0	33	919	3	1689
% TP mass below 6m	13%	45%	0%	2%	33%	1%	25%
% Volume below 6m	8%	30%	0%	2%	18%		
% increase to [TP] by including <6m	16%	29%	0%	0%	22%	0%	13%
May							
% dilution	23	4	31	1	4	3	7
TP concentration in whole column (ug/L)	**55**	**63**	**51**	**68**	**61**	**57**	**62**
TP concentration below 6m (ug/L)	84	81	0	73	90	63	85
TP concentration above 6m (ug/L)	48	39	51	66	44	57	58
TP mass in whole column (kg)	482	1457	80	1544	2678	451	6714
TP mass below 6m (kg)	58	552	0	29	736	3	1379
% TP mass below 6m	12%	38%	0%	2%	27%	1%	21%
% Volume below 6m	8%	29%	0%	2%	19%		
% increase to [TP] by including <6m	14%	61%	0%	2%	38%	0%	7%
June							
% dilution	31	16	37	4	15	12	14
TP concentration in whole column (ug/L)	**50**	**58**	**43**	**68**	**59**	**48**	**59**
TP concentration below 6m (ug/L)	83	85	0	79	100	52	93
TP concentration above 6m (ug/L)	44	33	43	67	40	48	53
TP mass in whole column (kg)	449	1340	69	1575	2583	382	6396
TP mass below 6m (kg)	58	580	0	32	824	3	1496
% TP mass below 6m	13%	43%	0%	2%	32%	1%	23%
% Volume below 6m	8%	30%	0%	2%	19%		
% increase to [TP] by including <6m	15%	76%	0%	2%	47%	0%	11%
July							
% dilution	17	11	18	4	9	7	8.9
TP concentration in whole column (ug/L)	**57**	**67**	**53**	**66**	**65**	**42**	**63**
TP concentration below 6m (ug/L)	134	127	0	110	150	59	138
TP concentration above 6m (ug/L)	47	29	53	64	37	42	50
TP mass in whole column (kg)	506	1518	85	1521	2826	328	6787
TP mass below 6m (kg)	93	867	0	44	1223	3	2236
% TP mass below 6m	18%	57%	0%	3%	43%	1%	33%
% Volume below 6m	8%	30%	0%	2%	19%		
% increase to [TP] by including <6m	22%	133%	0%	3%	76%	0%	27%
August							
% dilution	13	7	14	3	6	6	6
TP concentration in whole column (ug/L)	**59**	**69**	**48**	**67**	**67**	**45**	**65**
TP concentration below 6m (ug/L)	123	126	0	86	150	56	137
TP concentration above 6m (ug/L)	50	32	48	66	40	45	53
TP mass in whole column (kg)	541	1600	82	1602	2999	378	7208
TP mass below 6m (kg)	85	856	0	34	1229	3	2203
% TP mass below 6m	16%	53%	0%	2%	41%	1%	31%
% Volume below 6m	8%	30%	0%	2%	18%		
% increase to [TP] by including <6m	19%	115%	0%	2%	69%	0%	23%
September							
% dilution	9	5	8	2	5	7	5
TP concentration in whole column (ug/L)	**59**	**61**	**48**	**70**	**61**	**54**	**62**
TP concentration below 6m (ug/L)	65	69	0	61	69	56	69
TP concentration above 6m (ug/L)	54	41	48	69	48	54	61
TP mass in whole column (kg)	548	1435	83	1684	2734	457	6941
TP mass below 6m (kg)	45	469	0	25	568	3	1110
% TP mass below 6m	8%	33%	0%	1%	21%	1%	16%
% Volume below 6m	7%	29%	0%	2%	18%		
% increase to [TP] by including <6m	9%	49%	0%	1%	26%	0%	2%

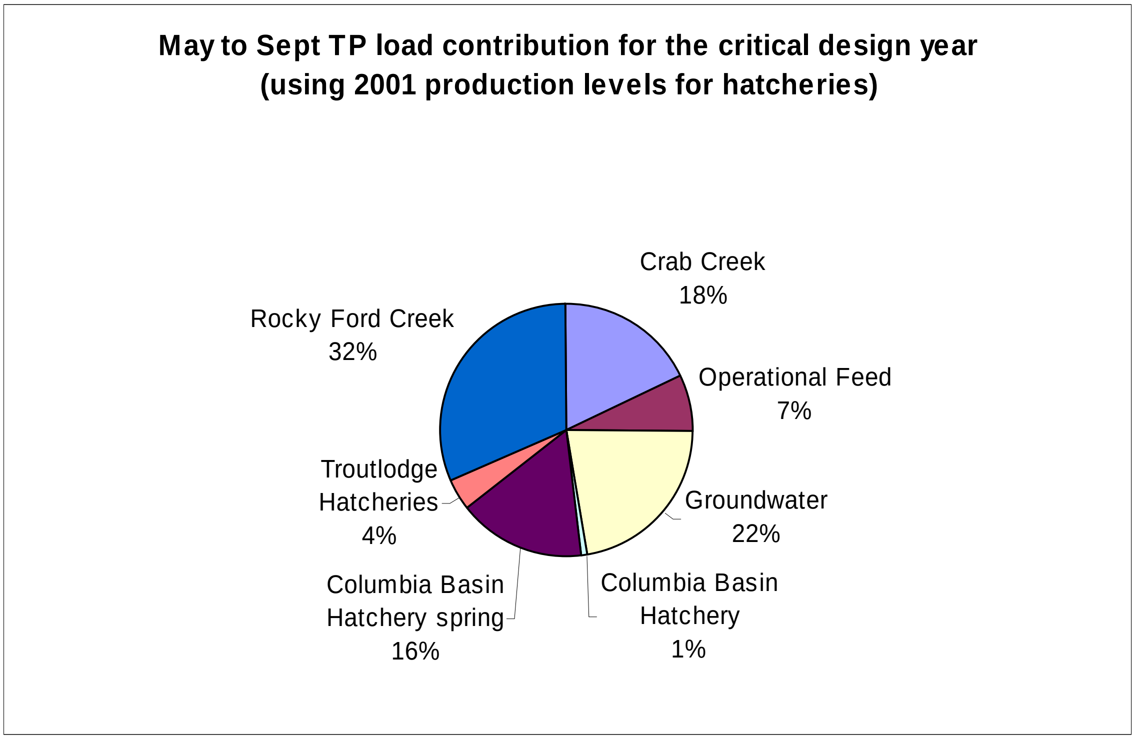


Figure 61. Pie diagram showing percent contributions of external TP sources during critical load conditions.

Next, the critical load conditions were modeled with the addition of a 50th percentile feed water flow. The feed water flow for 1982 represented this median flow. The feed water was added to the lake at the same rate as in 1982. A summary of results are presented in Table 16. A 50th percentile operational flow was predicted to reduce the TP concentration of the lake enough to meet the 50 ug/L criterion. The whole lake was predicted to have an average of 27% feed water during the May through September season. This further confirms the results from Welch et al. (1989) which found that the water quality goals are met when adequate dilution is available. The amount of feed water delivered to Moses Lake in this scenario was approximately half the amount delivered in 2001 or just over one lake volume (Figure 31). An addition of this much feed water in a critical flow year such as 1980 would require an operational change from the USBR normal operating procedures, but warrants consideration.

In the absence of an adequate feed water addition, a TP load reduction is necessary to meet the 50 ug/L TP criterion. As an initial allocation strategy, ortho-P and organic phosphorus were reduced by an equal percentage from all manageable phosphorus loading sources during the May through September critical season until the TP criterion was met.

Crab Creek, Rocky Ford Creek, and the Rocky Coulee Wasteway baseflow are supplied by groundwater emerging as springs during the summer. Groundwater also directly enters Moses Lake. All of these groundwater sources affect algae growth in Moses Lake during the critical season of concern by replenishing nutrients to the lake. All are considered manageable sources

Table 16. Summary of CE-QUAL-W2 modeling results for critical load conditions with a 50th percentile addition of feed water. All results are means for the specified time period and location.

	Branch 1 Parker Horn	Branch 2 South Basin	Branch 3 Lewis Horn	Branch 4 upper Rocky Ford Arm	Branch 4 lower Rocky Ford Arm	Branch 5,6,7,8 Pelican Horn	Whole Lake
May to September							
% dilution	48	35	50	10	28	25	27
TP concentration in whole column (ug/L)	**40**	**39**	**33**	**62**	**50**	**36**	**48**
TP concentration below 6m (ug/L)	79	53	0	72	95	37	76
TP concentration above 6m (ug/L)	34	34	33	62	40	36	44
TP mass in whole column (kg)	367	910	55	1442	2236	292	5312
TP mass below 6m (kg)	55	360	0	29	778	2	1223
% TP mass below 6m	15%	40%	0%	2%	35%	1%	23%
% Volume below 6m	8%	30%	0%	2%	18%		
% increase to [TP] by including <6m	17%	17%	0%	0%	25%	0%	11%
May							
% dilution	63	35	73	10	30	25	32
TP concentration in whole column (ug/L)	**34**	**43**	**26**	**61**	**47**	**42**	**47**
TP concentration below 6m (ug/L)	65	56	0	61	73	45	65
TP concentration above 6m (ug/L)	29	27	26	60	33	42	44
TP mass in whole column (kg)	298	994	42	1401	2045	333	5116
TP mass below 6m (kg)	45	379	0	25	599	2	1050
% TP mass below 6m	15%	38%	0%	2%	29%	1%	21%
% Volume below 6m	8%	30%	0%	2%	19%		
% increase to [TP] by including <6m	18%	62%	0%	2%	41%	0%	7%
June							
% dilution	69	50	72	14	40	36	39
TP concentration in whole column (ug/L)	**31**	**34**	**27**	**62**	**45**	**33**	**44**
TP concentration below 6m (ug/L)	54	43	0	69	74	33	60
TP concentration above 6m (ug/L)	27	22	27	61	31	33	41
TP mass in whole column (kg)	274	792	43	1433	1975	260	4772
TP mass below 6m (kg)	37	294	0	28	604	2	965
% TP mass below 6m	14%	37%	0%	2%	31%	1%	20%
% Volume below 6m	8%	30%	0%	2%	19%		
% increase to [TP] by including <6m	16%	59%	0%	2%	44%	0%	7%
July							
% dilution	61	45	60	11	35	30	33.4
TP concentration in whole column (ug/L)	**38**	**38**	**32**	**60**	**51**	**30**	**47**
TP concentration below 6m (ug/L)	108	61	0	92	124	30	95
TP concentration above 6m (ug/L)	29	19	32	59	28	30	39
TP mass in whole column (kg)	333	861	51	1372	2235	233	5105
TP mass below 6m (kg)	74	414	0	37	1019	2	1537
% TP mass below 6m	22%	48%	0%	3%	46%	1%	30%
% Volume below 6m	8%	30%	0%	2%	19%		
% increase to [TP] by including <6m	29%	93%	0%	3%	84%	0%	22%
August							
% dilution	32	30	32	10	24	22	21
TP concentration in whole column (ug/L)	**49**	**42**	**39**	**61**	**57**	**34**	**52**
TP concentration below 6m (ug/L)	109	63	0	78	139	37	103
TP concentration above 6m (ug/L)	41	23	39	60	32	34	43
TP mass in whole column (kg)	449	971	65	1458	2560	288	5798
TP mass below 6m (kg)	75	427	0	31	1128	2	1670
% TP mass below 6m	17%	44%	0%	2%	44%	1%	29%
% Volume below 6m	8%	29%	0%	2%	18%		
% increase to [TP] by including <6m	20%	78%	0%	2%	79%	0%	20%
September							
% dilution	15	16	12	6	13	14	11
TP concentration in whole column (ug/L)	**51**	**40**	**41**	**64**	**53**	**41**	**51**
TP concentration below 6m (ug/L)	57	42	0	57	64	38	54
TP concentration above 6m (ug/L)	47	28	41	64	41	41	51
TP mass in whole column (kg)	480	931	71	1550	2362	348	5766
TP mass below 6m (kg)	39	284	0	23	526	2	873
% TP mass below 6m	8%	30%	0%	1%	22%	1%	15%
% Volume below 6m	7%	29%	0%	2%	18%		
% increase to [TP] by including <6m	9%	44%	0%	1%	29%	0%	1%

and can be reduced. The water quality of the groundwater in the Moses Lake area is directly affected by land-use practices in the Moses Lake watershed. These include agricultural sources (fertilizers, irrigation, and animals) and urban sources around the lake. Pitz (2003) has shown that the magnitude of phosphorus loading from groundwater to Moses Lake is variable, with the highest phosphorus loading associated with urban development. The reservoir of phosphorus already in groundwater may persist for a long time, but efforts should be made to reduce further loading.

In addition to these nonpoint sources, there are four permitted point sources. They are all fish-rearing operations: the Columbia Basin Hatchery discharging through Rocky Coulee Wasteway, the two Troutlodge fish hatcheries on Rocky Ford Creek, and a state Department of Fish and Wildlife net pen facility in Moses Lake. The net pen facility is in operation only during the winter, so it does not have a direct impact on algae growth in the summer. The other three facilities are direct sources of nutrients to Moses Lake year-round and are manageable sources.

Internal loading was considered an uncontrollable source of TP to Moses Lake, although considering internal loading as uncontrollable also builds in a margin of safety because eventually internal loads would be suppressed after external loads were reduced on a long-term basis. Apparently internal loading is already suppressed from rates observed since the 1980s.

Without dilution, a 35% reduction in phosphorus from all manageable sources of phosphorus is predicted to most closely meet the proposed 50 ug/L criterion in all branches of the lake (Table 17). The whole-lake May through September mean TP is predicted to be 47 ug/L with a 35% external load reduction of phosphorus, but the South basin still had a May through September mean TP of 51 ug/L because of internal loading from the basin. Further load reduction is predicted to bring diminishing returns in reducing TP concentrations, because internal loading begins to be the dominating phosphorus source. The South basin was the most critical location for TP reduction due to this effect. Interestingly, if a 35% external reduction is achieved, the mean TP concentration in the whole lake above 6 meters, including the South basin, is predicted to be approximately 39 ug/L (conveniently close in agreement with the EPA TP criterion recommendation of 35 ug/L) if there is no internal load feedback. This indicates years with a low-mixing critical season (i.e., not a windy summer) will experience comparable water quality to, generally, the good water quality conditions of 2001.

Because of the dominating effect of internal loading after external load reduction, it is probably impractical to set a TP criterion any lower than the proposed 50 ug/L. It would be impossible to meet a lower TP criterion (e.g., 35 ug/L) without controlling internal loading.

Table 18 presents the May through September external TP loads during critical load conditions and the allocated maximum loads resulting after a 35% across-the-board reduction in TP load.

Table 17. Summary of CE-QUAL-W2 modeling results for critical load conditions with a 35% reduction of phosphorus from controllable external loads. All results are means for the specified time period and location.

	Branch 1 Parker Horn	Branch 2 South Basin	Branch 3 Lewis Horn	Branch 4 upper Rocky Ford Arm	Branch 4 lower Rocky Ford Arm	Branch 5,6,7,8 Pelican Horn	Whole Lake
May to September							
% dilution	19	9	22	3	8	7	8
TP concentration in whole column (ug/L)	**41**	**51**	**33**	**46**	**48**	**35**	**47**
TP concentration below 6m (ug/L)	85	85	0	67	99	44	92
TP concentration above 6m (ug/L)	35	37	33	46	37	35	39
TP mass in whole column (kg)	374	1185	55	1072	2137	282	5110
TP mass below 6m (kg)	59	580	0	27	811	2	1481
% TP mass below 6m	16%	49%	0%	2%	38%	1%	29%
% Volume below 6m	8%	29%	0%	2%	19%		
% increase to [TP] by including <6m	19%	38%	0%	1%	31%	0%	20%
May							
% dilution	23	4	31	1	4	3	7
TP concentration in whole column (ug/L)	**43**	**52**	**37**	**53**	**49**	**44**	**49**
TP concentration below 6m (ug/L)	73	71	0	63	79	53	75
TP concentration above 6m (ug/L)	37	31	37	52	35	44	45
TP mass in whole column (kg)	378	1183	59	1210	2158	346	5348
TP mass below 6m (kg)	51	483	0	25	645	3	1207
% TP mass below 6m	13%	41%	0%	2%	30%	1%	23%
% Volume below 6m	8%	30%	0%	2%	19%		
% increase to [TP] by including <6m	15%	69%	0%	2%	43%	0%	10%
June							
% dilution	31	16	37	4	15	12	14
TP concentration in whole column (ug/L)	**38**	**47**	**31**	**48**	**46**	**35**	**45**
TP concentration below 6m (ug/L)	72	74	0	66	89	41	81
TP concentration above 6m (ug/L)	33	26	31	47	30	35	39
TP mass in whole column (kg)	340	1100	50	1114	2032	275	4923
TP mass below 6m (kg)	50	502	0	26	732	2	1312
% TP mass below 6m	15%	46%	0%	2%	36%	1%	27%
% Volume below 6m	8%	29%	0%	2%	19%		
% increase to [TP] by including <6m	17%	84%	0%	2%	56%	0%	16%
July							
% dilution	17	11	18	4	9	7	8.9
TP concentration in whole column (ug/L)	**41**	**54**	**34**	**43**	**50**	**27**	**47**
TP concentration below 6m (ug/L)	124	115	0	97	140	45	127
TP concentration above 6m (ug/L)	31	20	34	41	24	27	33
TP mass in whole column (kg)	364	1227	55	983	2195	212	5046
TP mass below 6m (kg)	86	781	0	39	1143	2	2052
% TP mass below 6m	24%	64%	0%	4%	52%	1%	41%
% Volume below 6m	8%	30%	0%	2%	19%		
% increase to [TP] by including <6m	31%	175%	0%	4%	109%	0%	43%
August							
% dilution	13	7	14	3	6	6	6
TP concentration in whole column (ug/L)	**42**	**55**	**32**	**42**	**51**	**30**	**47**
TP concentration below 6m (ug/L)	106	111	0	66	133	41	120
TP concentration above 6m (ug/L)	34	23	32	41	26	30	35
TP mass in whole column (kg)	388	1300	54	999	2265	250	5249
TP mass below 6m (kg)	73	754	0	26	1090	2	1949
% TP mass below 6m	19%	58%	0%	3%	48%	1%	37%
% Volume below 6m	8%	29%	0%	2%	18%		
% increase to [TP] by including <6m	23%	138%	0%	3%	93%	0%	36%
September							
% dilution	9	5	8	2	5	7	5
TP concentration in whole column (ug/L)	**43**	**47**	**33**	**44**	**45**	**38**	**44**
TP concentration below 6m (ug/L)	50	55	0	40	53	42	53
TP concentration above 6m (ug/L)	39	31	33	43	35	38	43
TP mass in whole column (kg)	398	1109	57	1053	2030	327	4977
TP mass below 6m (kg)	34	374	0	16	433	2	859
% TP mass below 6m	9%	34%	0%	2%	21%	1%	17%
% Volume below 6m	7%	29%	0%	2%	18%		
% increase to [TP] by including <6m	9%	51%	0%	2%	27%	0%	3%

Table 18. External TP load contributions to Moses Lake (May through September) during critical load conditions and TP loads following 35% load reduction.

External Source	TP (kg)	TP load after 35% reduction (kg)
Crab Creek	1765	1147
Operational Feed	687	447
Groundwater	2150	1398
Columbia Basin Hatchery[1]	77	50
Columbia Basin Hatchery spring	1582	1028
Troutlodge Hatcheries[1]	398	259
Rocky Ford Creek	3089	2008

[1]Hatcheries contributions based on 2001 production levels

Margin of Safety

There were a number of implicit margin of safety factors or conservative assumptions used to evaluate the TP TMDL capacity of Moses Lake. A margin of safety is included to account for uncertainty related to the estimation of loads and loading capacity of Moses Lake.

The following assumptions were considered implicit margins of safety in the data evaluation and modeling:

- When evaluating model simulations, the entire water column TP was averaged for compliance with the TP criterion. Even though the algae grow in the euphotic zone, the entire water column was averaged because Moses Lake is polymictic (i.e., capable of mixing several times during the growing season). The potential entrainment of elevated hypolimnetic concentrations of TP was considered a margin of safety and included in the available TP pool. The hypolimnion represents less than 20% of the volume of the lake. During May through September 2001, the average seasonal whole column TP was 24% more than the average seasonal euphotic zone TP in the whole lake. This could be considered an implicit 24% margin of safety and account for the natural variation (uncertainty) associated with internal loading which has been shown to have a variability of up to 100% (Welch et al., 1989).

- The hydraulic conditions of 1980 were chosen to model critical flow conditions. The year represents an approximate 90th percentile flow for inflows from Rocky Ford Creek and Crab Creek and a 10th percentile flow for feed water through Rocky Coulee Wasteway (based on flow records from 1977-2001). The probability of these conditions occurring is approximately one in ten years on average, which Ecology considers an acceptable exceedance probability (i.e., approximately 10%).

Conclusions

2000-01 Water Quality Study

The major findings of this report regarding the 2000-01 water quality study are as follows:

- Intensive sampling of Moses Lake and its vicinity was conducted from October 2000 through September 2001 (study period) to assess the status of the lake and its tributaries. In addition, a separate study of the water quality of groundwater directly entering Moses Lake was conducted (Pitz, 2003). The last intensive water quality study of Moses Lake was completed in 1988, summarized by Welch et al. (1989). This current report updates that work and complements the historical review and preliminary TMDL evaluation by Carroll et al. (2000).

- Rocky Ford Creek and Crab Creek experienced low-flow conditions during the 2000/01 study period. Accordingly, the U.S. Bureau of Reclamation (USBR) delivered a large amount of feed water through Moses Lake. This had the effect of diluting Moses Lake during 2001, resulting in lower total phosphorus (TP) mass and algal biomass.

- The mean TP concentration for May through September 2001 for the whole lake was 38 ug/L. This was below the proposed TP criterion threshold of 50 ug/L. There were no excessive blooms of blue-green algae that threatened the beneficial uses of Moses Lake during 2001.

- Groundwater discharging directly to Moses Lake was found to be a substantial source of phosphorus to the lake. It was estimated that 24% of the phosphorus load to Moses Lake from May through September 2001 came from direct groundwater flux. Pitz (2003) found higher concentrations of phosphorus in the groundwater than found in the past, particularly associated with up-gradient urban wastewater sources.

- It was estimated that background and in-creek sources of Rocky Ford Creek contributed a total of 32% of the phosphorus to Moses Lake from May through September 2001. Additionally, the fish hatcheries on Rocky Ford Creek were estimated to contribute 6% of the phosphorus during the same period.

- As of 2001, there is no indication that TP and ortho-P concentrations in Rocky Ford Creek have changed from measured historical concentrations, suggesting that the mechanisms of anthropogenic contamination of phosphorus are the same as before and that restoration measures applied to date, including the detention pond on Rocky Ford Creek, have not succeeded. Though Crab Creek TP and ortho-P concentrations have declined dramatically since 1969-70s (attributed to a switch from surface rill or furrow irrigation to sprinkler irrigation), May through September 2001 ortho-P concentrations in Crab Creek were slightly higher than those observed in the 1980s.

- There was no winter/spring runoff event in Crab Creek in 2001, so the water quality of such an event could not be characterized.

Phosphorus Modeling

The major findings of this report regarding the phosphorus modeling are as follows:

- A hydrodynamic, unsteady-state model of temperature and water quality, based on the CE-QUAL-W2 model, was developed for Moses Lake and calibrated to the 2001 water quality data. The model was used to evaluate the capacity of the lake to assimilate TP loads from point and nonpoint sources and meet the recommended water quality criterion.

- This report concurs with the recommendation by Carroll et al. (2000) to establish a water quality TP criterion of 50 ug/L for Moses Lake. This criterion should be applied to the critical season of concern, May through September, when blue-green algae blooms take place.

- Using critical load conditions, representing approximately a 90th percentile phosphorus load to the lake, the lake model showed that an across-the- board 35% load reduction in TP from Rocky Ford Creek, Crab Creek, Rocky Coulee Wasteway baseflow, and groundwater was necessary to meet the proposed TP criterion with only a one-in-ten-year chance on average of exceeding the criterion (10% exceedance probability). Further load reduction was predicted to bring diminishing returns in reducing TP concentrations in the lake because internal loading begins to dominate as a phosphorus source. The model indicated that it probably would be impossible to meet a lower TP criterion (e.g., 35 ug/L) without controlling internal loading.

- Internal sediment release of phosphorus is an important loading source to Moses Lake, though apparently not as important as in earlier years. Because Moses Lake is polymictic, nearly all of the phosphorus released from the sediments may be available in the epilimnion during the growing season. This presents a definite restoration limitation for Moses Lake and a continued indication that it will remain eutrophic. However, reductions in phosphorus loading should reduce sediment concentrations and improve water quality over time, as may have been seen in 2001.

- A variable mixture of Crab Creek winter/spring flow and USBR feed water determine the initial water quality conditions of Moses Lake in the spring. Initial conditions of the water column in Moses Lake at the start of the growing season are important as far as the extent and magnitude of the spring diatom bloom, but may not be as important in late summer algal production. The replenishment of phosphorus, particularly ortho-P, from the tributaries and groundwater is necessary to fuel summer algal growth.

- Sufficient feed water through Moses Lake (i.e., dilution flow) can mitigate the excessive nutrient loading and undesirable algae growth during the summer. The lake model showed that a 50th percentile feed water addition to Moses Lake during critical load conditions will reduce average TP concentration below the 50 ug/L criterion. If this level could be provided annually, then the criterion is predicted to be met every year with only a 10% exceedance probability.

Recommendations

The following recommendations address the issues related to TMDLs and management strategies for parameters on the 303(d) list:

Dilution Strategies for Moses Lake

Dilution has been critical to achieving the water quality goals in Moses Lake since 1977. However, currently feed water is not supplied every year due to operational infrastructure limitations and/or legal contractual constraints in spilling feed water. The U.S. Bureau of Reclamation (USBR) only provides dilution water on an "as available" basis, primarily when there is need for feed water in the southern part of the Columbia Basin Irrigation Project. Dilution is a beneficial restorative management technique and may be necessary to achieve water quality goals in the future because of the persistence of phosphorus in the local aquifer. More precise management of feed water may be important for retaining enough total phosphorus (TP) (i.e., algal biomass) in Moses Lake to limit the expansion of macrophytes in the lake.

Alternate ways of providing annual feed water (dilution water), especially throughout the critical season of May through September, should be explored with the USBR. Allocation of reliable feed water to Moses Lake will depend largely on local interest in improving the lake's water quality. In order to be considered a permanent restoration technique for Moses Lake, the delivery of dilution water needs to be reliable.

Nonpoint Control of Winter/Spring Runoff from Crab Creek

Historically, during certain years Crab Creek experiences large winter/spring runoff events. These events are unpredictable and vary in size, but large events (>500 cfs) have occurred in 40% of the last 40 years. These flow events carry large TP loads to Moses Lake., essentially flushing the Crab Creek store of nutrients into Moses Lake. Implementation of nonpoint controls and best management practices (BMPs) to improve the water quality of these watershed flushings is recommended. Examples would be the use of erosion controls and riparian buffers. BMPs might include better management of fertilizer application and irrigation water. Also testing of soils for phosphorus content may indicate the need for less phosphorus application.

The water quality of Crab Creek winter/spring runoff events should be characterized at the point where they enter Moses Lake and at points upstream to identify source reaches. Characterization should include sampling for TP, ortho-P, nitrate, ammonia, total organic carbon, dissolved organic carbon, total suspended solids, and total non-volatile suspended solids. At a minimum, sampling should occur over several days, trying to capture the beginning, peak, and end of the runoff event.

Reduction of Phosphorus from Diffuse Nonpoint Sources Supplying Baseflow to Moses Lake from May through September

Groundwater in the Moses Lake vicinity needs to be protected from further nutrient loading. Unidentified, diffuse, nonpoint sources supply phosphorus to the baseflow of Rocky Ford Creek, Crab Creek, Rocky Coulee Wasteway, and groundwater entering Moses Lake directly. A watershed-wide 35% reduction of phosphorus from these sources is recommended. The recommendations put forth by Pitz (2003) should be followed.

Increased on-site septic systems and near-shore development have the greatest impacts on groundwater quality in the vicinity of Moses Lake. It is recommended that the city of Moses Lake and Grant County work together to develop and adopt local ordinances to reduce these impacts. The Columbia Basin Groundwater Management Area (GWMA), currently working on reducing nitrate in groundwater, may be able to provide assistance and resources for reducing phosphorus in groundwater.

Irrigation and fertilizer controls as well as management to control phosphorus were initiated in the mid-1980s, concentrating on the Crab Creek watershed, but the study project concluded in 1990. It is recommended to continue the implementation of existing BMPs and apply more extensive BMPs on agricultural lands within the Moses Lake vicinity. Again, the GWMA may be able to provide assistance.

Reduction of Phosphorus from Point Sources

While controls are being designed for groundwater TP sources, TP limits for the fish hatcheries also should be established. The same 35% reduction in phosphorus recommended for nonpoint sources should be applied to fish hatcheries.

Nutrient limits for fish hatcheries on Rocky Ford Creek also may address the dissolved oxygen and pH listings for the creek. During the 2001 water quality study, the reaches immediately below the fish hatcheries on Rocky Ford Creek were more likely to violate dissolved oxygen standards.

Kendra (1989) and Cusimano and Ward (1998) recommended that phosphorus reduction could be achieved through reduced fish production during critical seasons. For Moses Lake this would be May through September. Also the use of low-phosphorus feed and decreased food wastage may reduce phosphorus. In some cases, enhanced wastewater treatment may be required. The Columbia Basin Hatchery should clean their abatement pond more regularly. Personnel for the state Department of Fish and Wildlife indicated they are considering installing a new wastewater treatment system for the Columbia Basin Hatchery. Kendra (1989) also lists operational BMPs to reduce solids.

Upstream and downstream phosphorus monitoring during May through September should be required of the hatcheries and reported in the discharge monitoring report.

References

Aroner, E., 1994. WQHYDRO: Water Quality/Hydrology Graphics/Analysis System. April 1994. P.O. Box 18149, Portland, OR.

Bain, R.C., Jr., 1998. Moses Lake Area: Water Quality Monitoring Report (1997). Prepared for the Moses Lake Irrigation & Rehabilitation District, Moses Lake, WA.

Bostrom, B., M. Jansson, and C. Forsberg, 1982. Phosphorus release from lake sediments. Arch. Hydrobiol. Beih. Ergebn. Limnol., 18: 5-59, Stuttgart. November 1982.

Carroll, J.V., 2001. Moses Lake Phosphorus TMDL Study. Quality Assurance Project Plan. Washington State Department of Ecology, Olympia, WA.

Carroll, J.V., R.F. Cusimano, and W.J. Ward, 2000. Moses Lake Proposed Phosphorus Criterion and Preliminary Load Allocations Based on Historical Review. Washington State Department of Ecology, Olympia, WA. Publication No. 00-03-036. http://www.ecy.wa.gov/biblio/0003036.html.

Chapra, S.E., 1997. Surface Water-Quality Modeling. WCB McGraw-Hill, Boston, MA.

Cohn, T.A., L.L. DeLong, E.J. Gilroy, R.M. Hirsch, and D.K. Wells, 1989. Estimating constituent loads. Water Resources Research, v. 25, no. 5, p. 937-942.

Cole and Wells, 2002. CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.1. Users Manual (Draft Report). Prepared for the U.S. Army Corps of Engineers, Washington, DC. Instructional Report EL-02-1. August 2002.

Cusimano and Ward, 1998. Rocky Ford Creek TMDL Study. Washington State Department of Ecology, Watershed Ecology Section, Olympia, WA. Publication No. 98-326.

Ehinger, W., 1996. Freshwater Ambient Water Quality Monitoring. Final Quality Assurance Project Plan. Washington State Department of Ecology, Olympia, WA. June 1996.

EPA, 1985. Rates, Constants, and Kinetics Formulations in Surface Water Quality Modeling (Second Edition). EPA/600/3-85/040. U.S. Environmental Protection Agency, Athens, GA.

EPA, 1987. The Enhanced Water Quality Models QUAL2E and QUAL2E-UNCAS: Documentation and users manual. EPA/600/3-87/007. U.S. Environmental Protection Agency.

EPA, 2001. Ambient Water Quality Criteria Recommendations. Information Supporting the Development of State and Tribal Nutrient Criteria for Lakes and Reservoirs in Nutrient Ecoregion III (Xeric West). EPA-822-B-01-008. U.S. Environmental Protection Agency, Washington DC. December 2001.

Horner, R.R., E.B. Welch, M.M. Wineman, M.J. Adolfson, and R.C. Bain Jr., 1985. Nutrient Transport Processes in an Agricultural Watershed. Proceedings from the Fourth Annual Conference of the North American Lake Management Society, October 1984, McAfee, NJ.

Jones, C.A. and E.B. Welch, 1990. Internal phosphorus loading related to mixing and dilution in a dendritic, shallow prairie lake. Res. J. Water Pollut. Control Fed., 62, 847-852.

Kendra, W., 1989. Quality and Fate of Fish Hatchery Effluents During the Summer Low Flow Season. Washington State Department of Ecology, Olympia, WA. Publication No. 89-17.

Korth, J., 2002. Personal communication. Washington State Department of Fish and Wildlife, Olympia, WA. June 18.

Lombard, S. and C. Kirchmer, 2001. Guidelines for Preparing Quality Assurance Project Plans for Environmental Studies. Washington State Department of Ecology, Olympia, WA. Publication No. 01-03-003.

MEL, 2000. Lab Users Manual. Manchester Environmental Laboratory, Washington State Department of Ecology, Manchester, WA.

Parsons, J., 2002. Personal communication. Troutlodge, Inc., Soap Lake, WA. E-mail transmittal on 12/5/02.

Patmont, C.R., 1980. Phytoplankton and nutrient responses to dilution in Moses Lake. Masters Thesis, University of Washington, Department of Civil Engineering, Seattle, WA.

Pitz, C.F., 2003. Moses Lake Total Maximum Daily Load Groundwater Study. Washington State Department of Ecology, Olympia, WA. Publication No. 03-03-005. http://www.ecy.wa.gov/biblio/0303005.html

Reckhow, K.H., 1986. Statistical goodness-of-fit measures for waste load allocation models. Work Assignment No. 33. EPA Contract No. 68-01-6904. September 1986.

Reynolds, C.S., 1984. The Ecology of Freshwater Phytoplankton. Cambridge University Press, New York, NY.

Smith, B., 2001. Personal communication. U.S. Geological Survey, Spokane, WA.

Sylvester, R.O., and R.T. Oglesby, 1964. The Moses Lake Water Environment. University of Washington, Department of Civil Engineering, Seattle, WA.

WAS, 1993. Field Sampling and Measurement Protocols for the Watershed Assessments Section. Washington State Department of Ecology, Olympia, WA. Publication No. 93-e04.

Welch, E.B., R.M. Bush, D.E. Spyridakis, and M.B. Saikewicz, 1973. Alternatives for Eutrophication Control in Moses Lake, Washington. Report prepared for the Moses Lake Irrigation and Rehabilitation District. University of Washington, Department of Civil Engineering, Seattle, WA.

Welch, E.B., C.A. Jones, and R.P Barbiero, 1989. Moses Lake Quality: Results of Dilution, Sewage Diversion and BMPs – 1977 through 1988. University of Washington, Department of Civil Engineering, Water Resources Technical Report 118.

Welch, E.B., R.P. Barbiero, D. Bouchard, and C.A. Jones, 1992. Lake trophic state change and constant algal composition following dilution and diversion. Ecological Engineering, 1 (1992) 173-197.

Wetzel, R.G., 1983. Limnology. W.B. Saunders Co., Philadelphia, PA. 753 pp.

Witt, B., 2002. Personal communication. Hatchery manager, Troutlodge, Inc., Soap Lake, WA. 10/18/02.